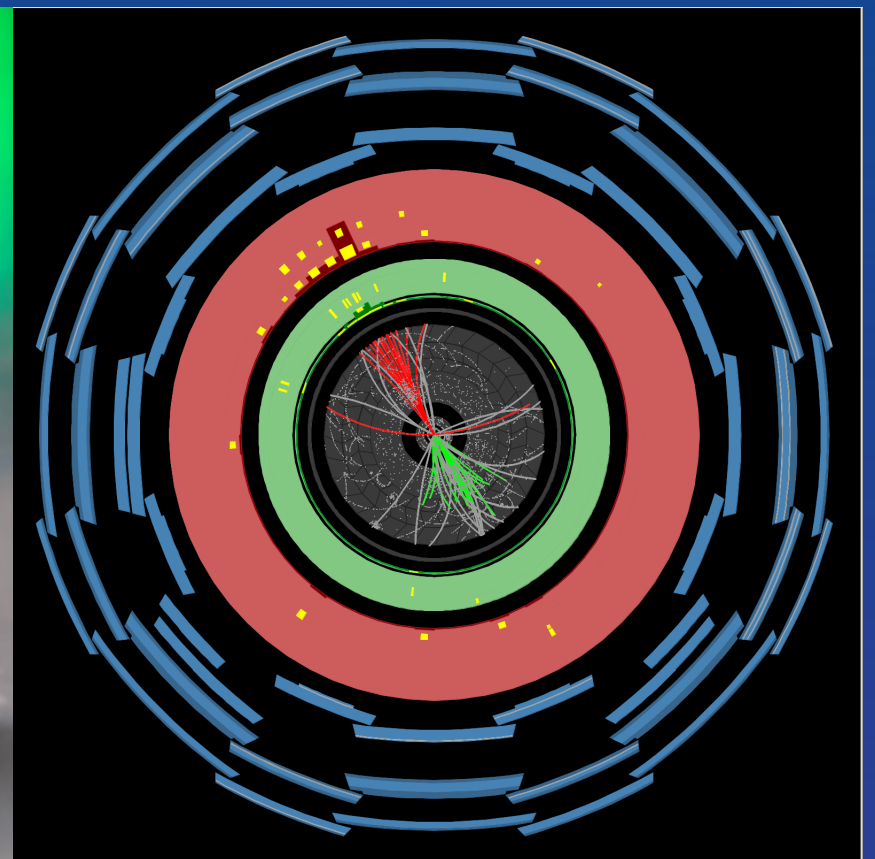


The Coming Revolutions in Particle Physics

Chris Quigg

Fermi National Accelerator Laboratory



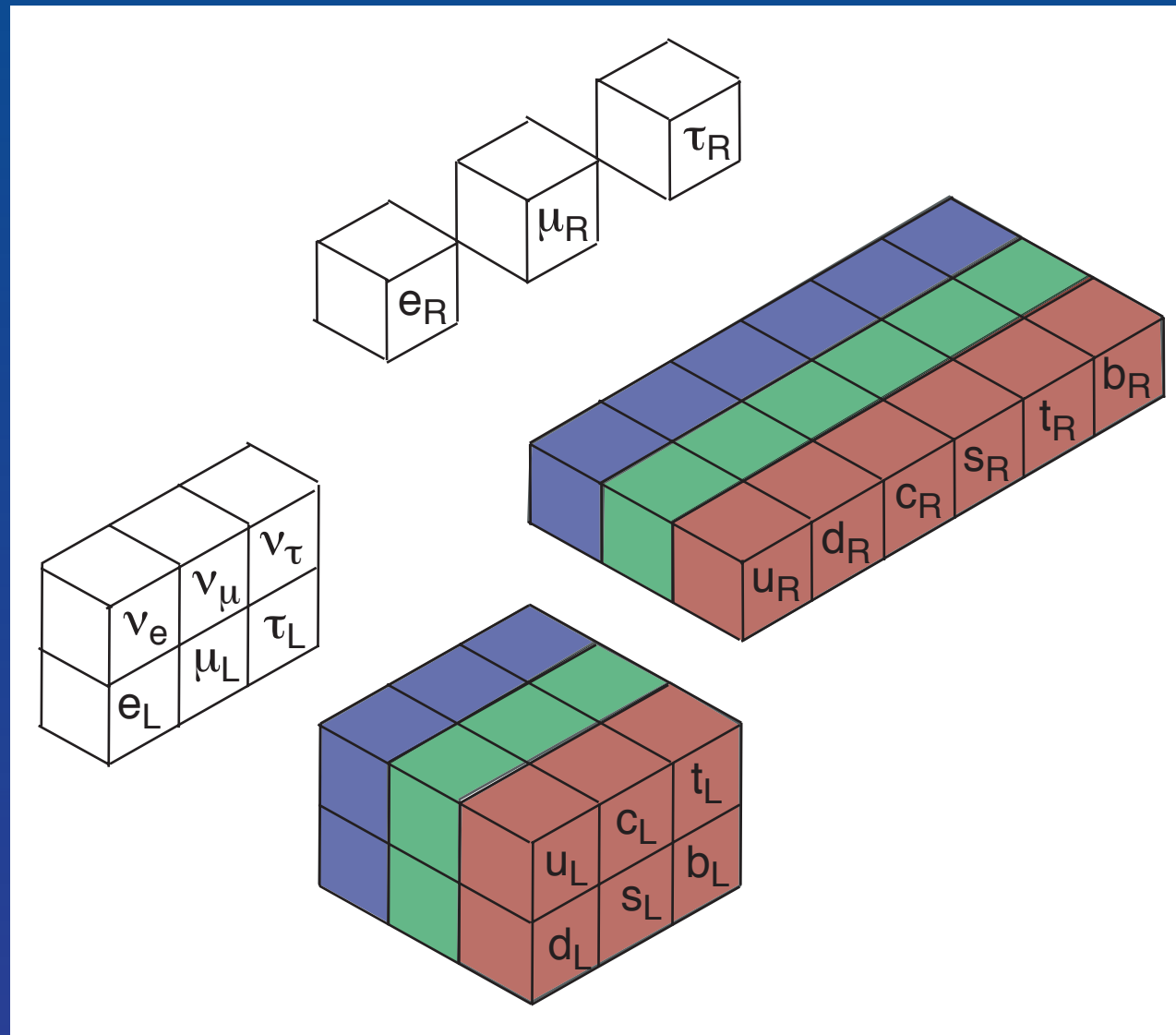
Universe Colloquium · 20 October 2010

A Decade of Discovery Past

- ▷ Electroweak theory \rightarrow law of nature [Z , e^+e^- , $\bar{p}p$, νN , $(g-2)_\mu$, ...]
- ▷ Higgs-boson influence observed in the vacuum [EW experiments]
- ▷ Neutrino flavor oscillations: $\nu_\mu \rightarrow \nu_\tau$, $\nu_e \rightarrow \nu_\mu/\nu_\tau$ [ν_\odot , ν_{atm}]
- ▷ Understanding QCD [heavy flavor, Z^0 , $\bar{p}p$, νN , ep , lattice]
- ▷ Discovery of top quark [$\bar{p}p$]
- ▷ Direct CP violation in $K \rightarrow \pi\pi$ decay [fixed-target]
- ▷ B -meson decays violate CP [$e^+e^- \rightarrow B\bar{B}$]
- ▷ Flat universe dominated by dark matter & energy [SN Ia, CMB, LSS]
- ▷ Detection of ν_τ interactions [fixed-target]
- ▷ Quarks & leptons structureless at TeV scale [mainly colliders]

Our Picture of Matter (the revolution just past)

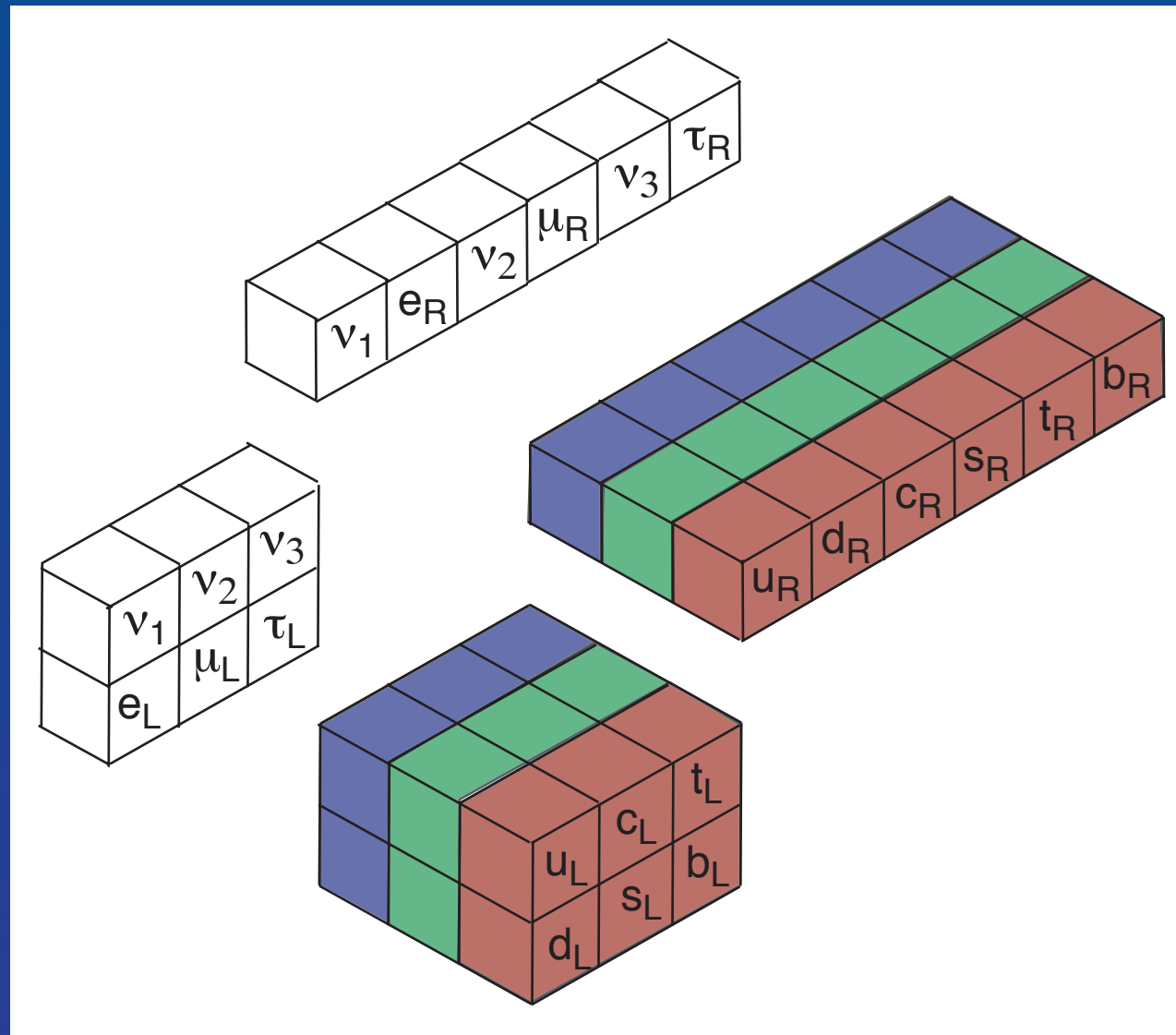
Pointlike ($r \leq 10^{-18}$ m) *quarks* and *leptons*



Interactions: $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ gauge symmetries

Our Picture of Matter (the revolution just past)

Pointlike ($r \leq 10^{-18}$ m) *quarks* and *leptons*



Interactions: $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ gauge symmetries



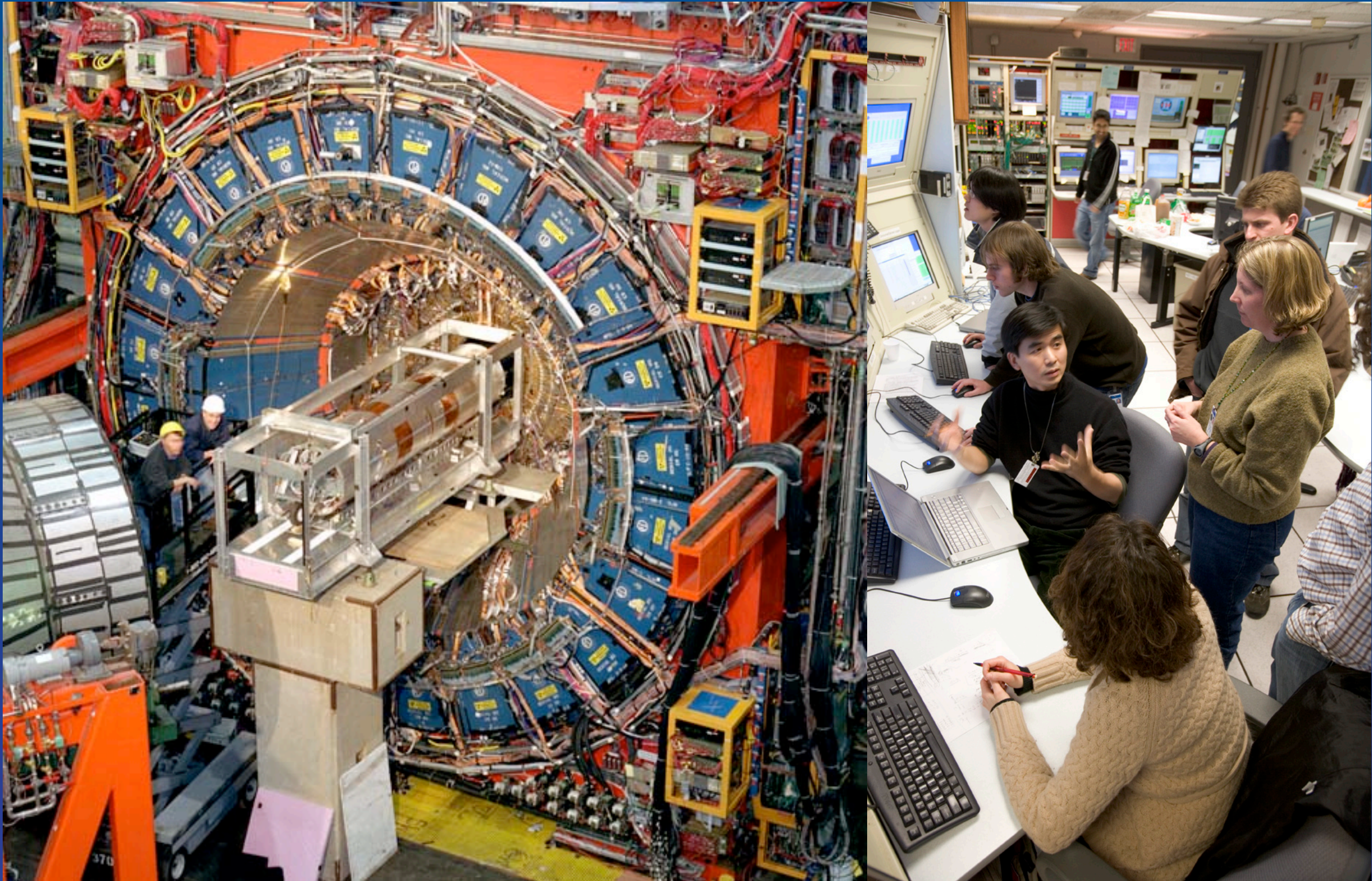
The world's most powerful microscopes
... home to *nanonano*physicists!

Tevatron collider at Fermilab
protons on antiprotons at 1+1 TeV
speed of light: $c \approx 10^9$ km/h
speed of protons: $c - 495$ km/h

Protons pass my window 45,000 times / second
>10 million collisions per second

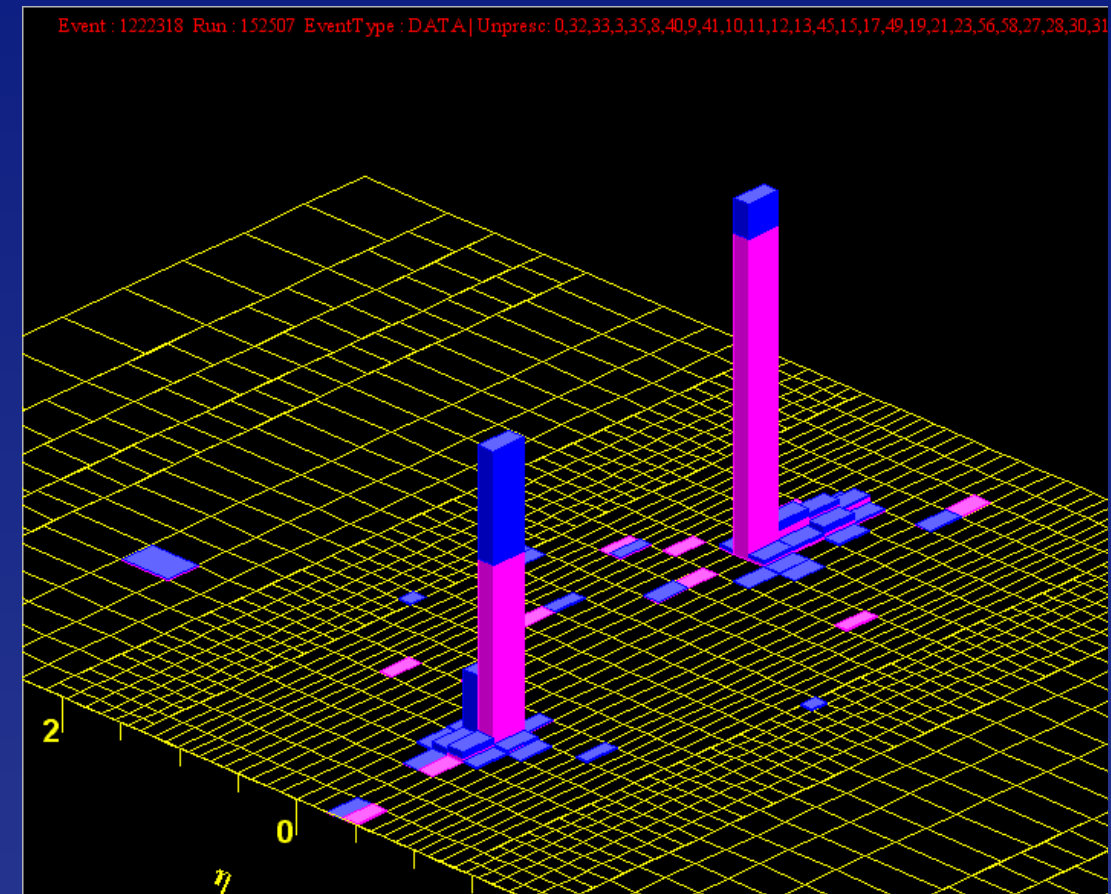
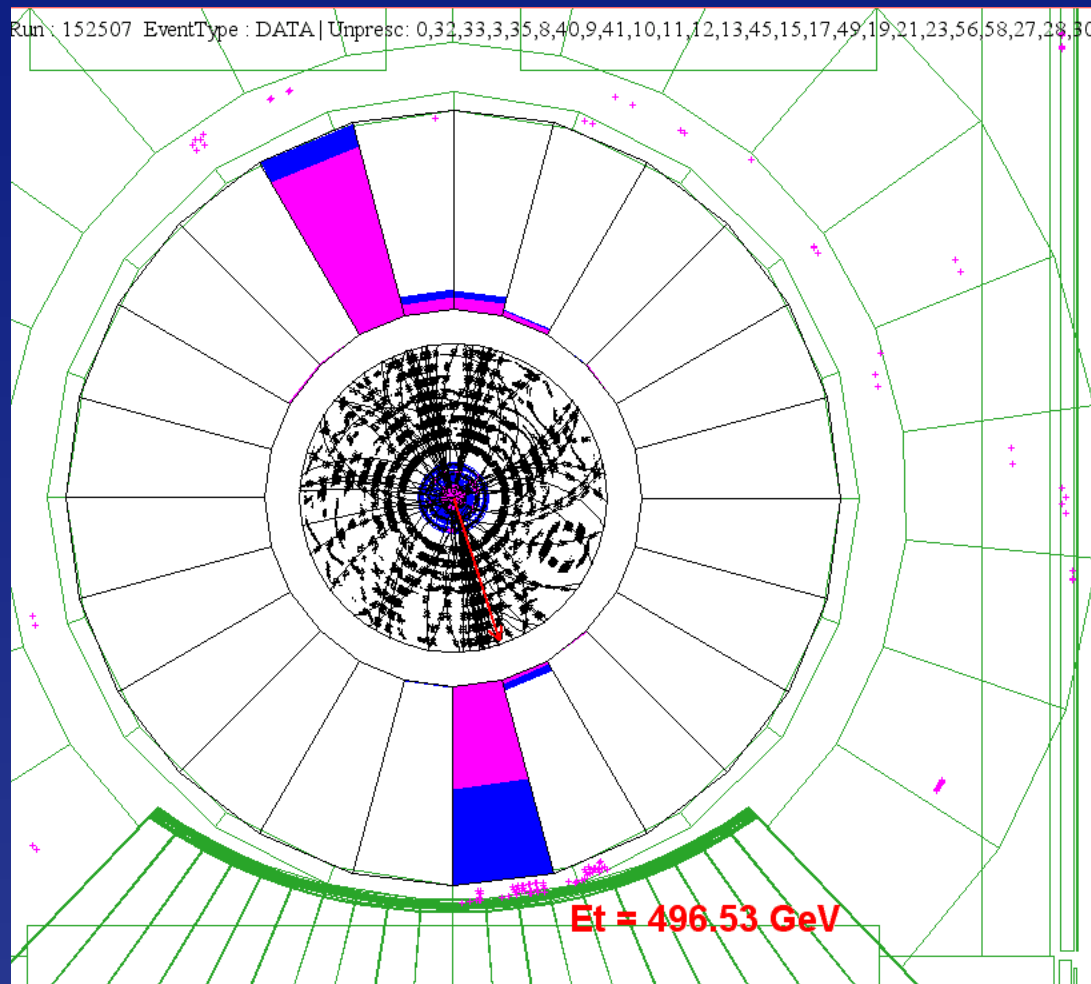
speed of protons in the LHC now: $c - 39$ km/h
soon: $c - 10$ km/h

CDF Experiment



The World's Most Powerful Microscopes

nanonanophysics

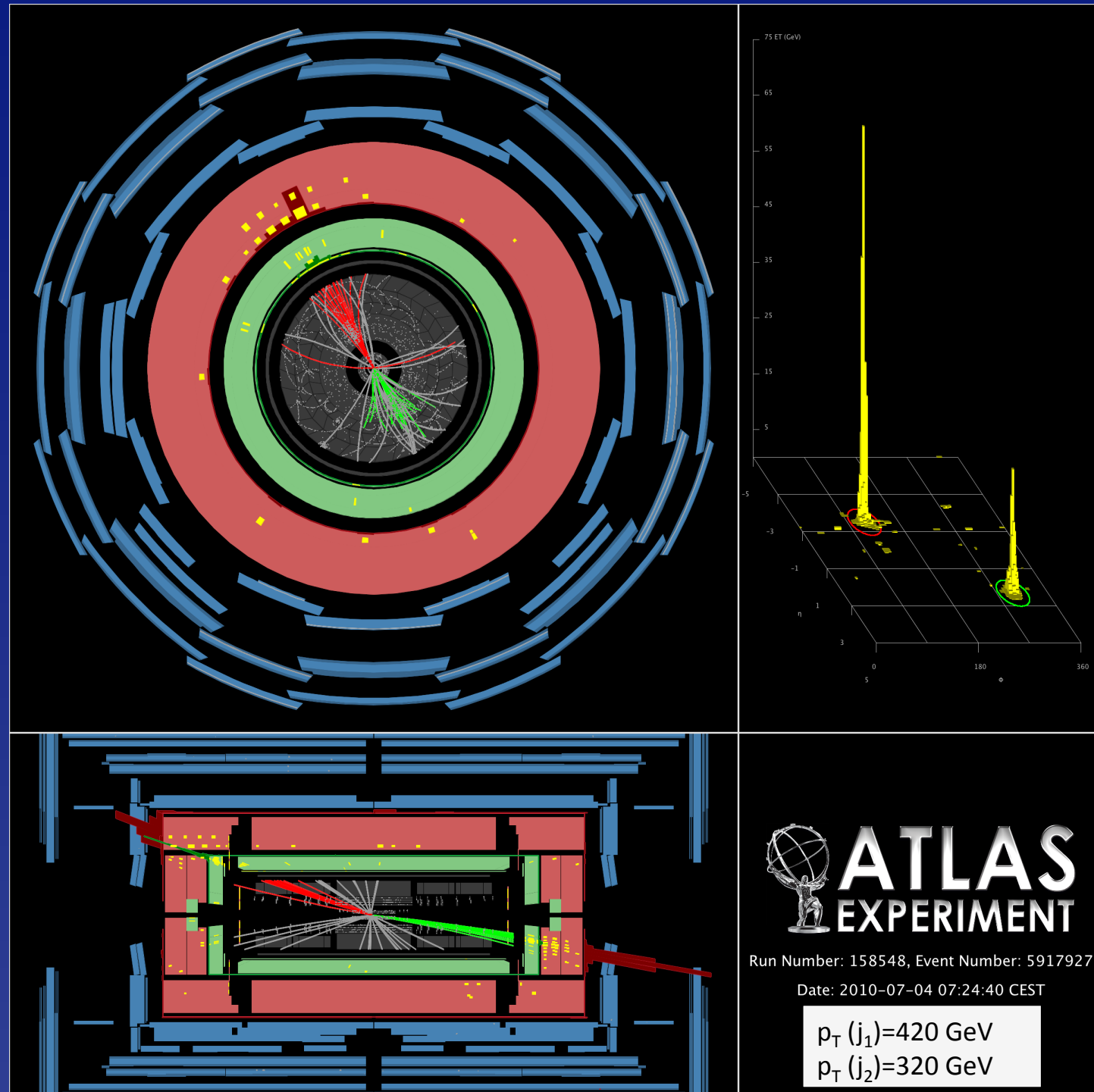


CDF two-jet event (70% of energy \perp beam direction)

quark + antiquark \rightarrow jet + jet

The World's Most Powerful Microscopes

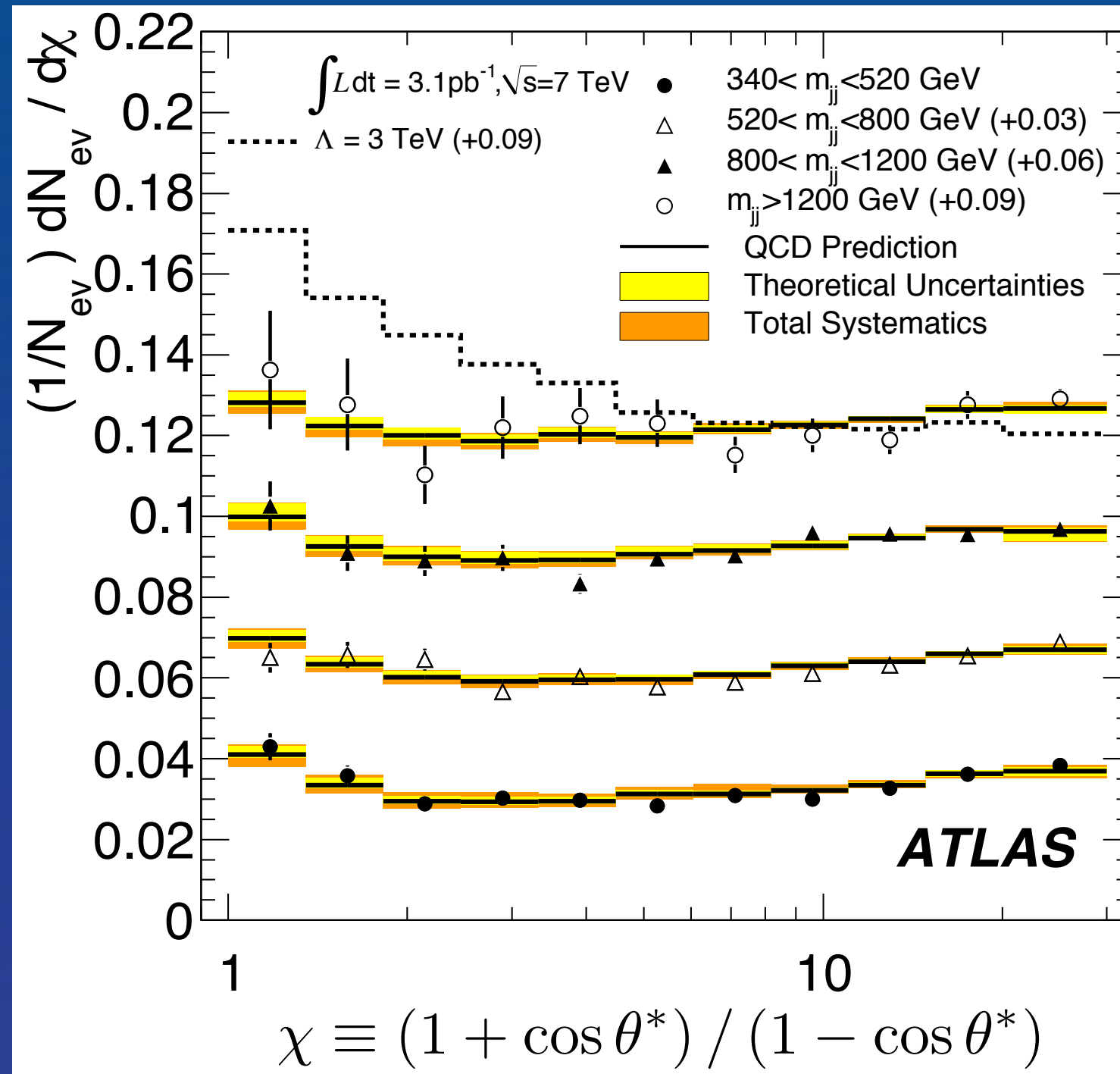
nanonanophysics



Dijet mass: 2.55 TeV

The World's Most Powerful Microscopes

nanonanophysics

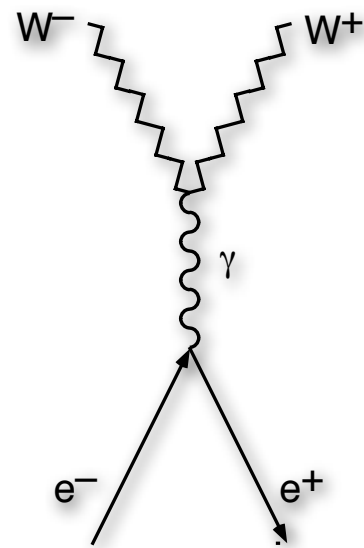


(quark radius < 1 am)

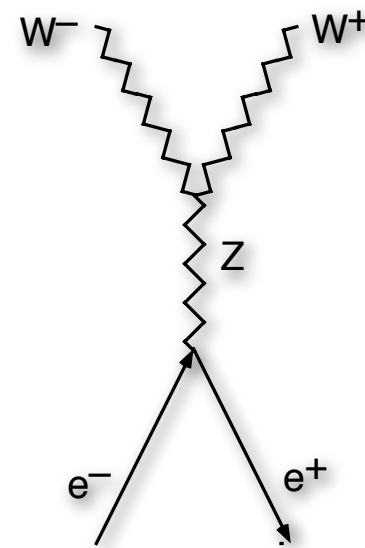
arXiv:1009.5069

Gauge symmetry (group-theory structure) tested in

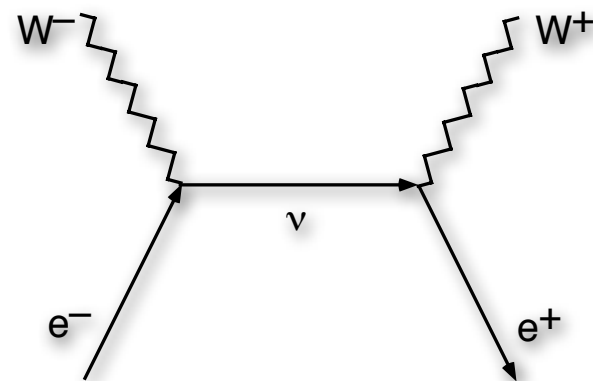
$$e^+e^- \rightarrow W^+W^-$$



(a)



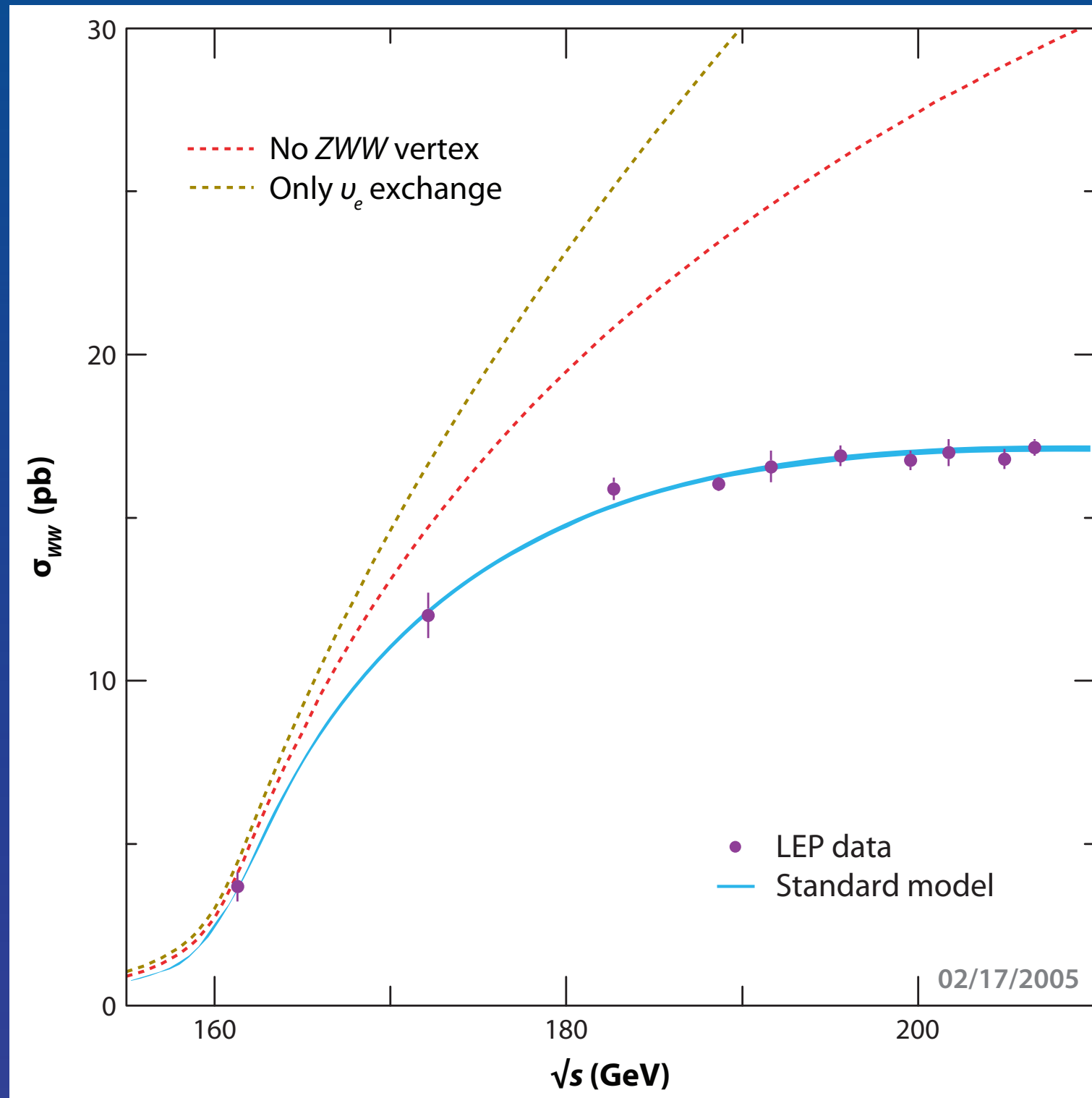
(b)



(c)

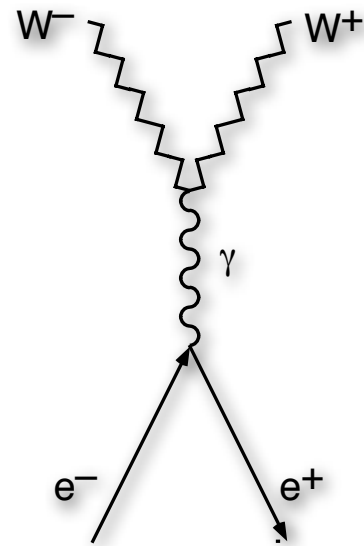
Gauge symmetry (group-theory structure) tested in

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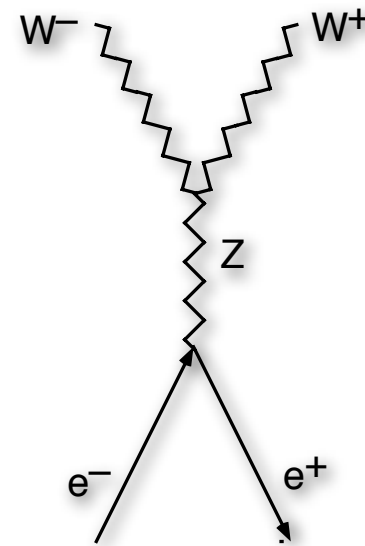


Gauge symmetry (group-theory structure) tested in

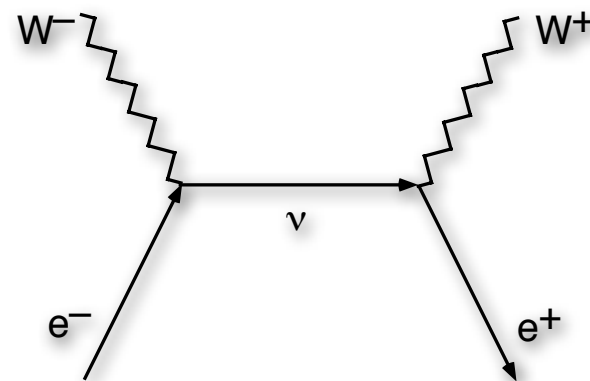
$$e^+e^- \rightarrow W^+W^-$$



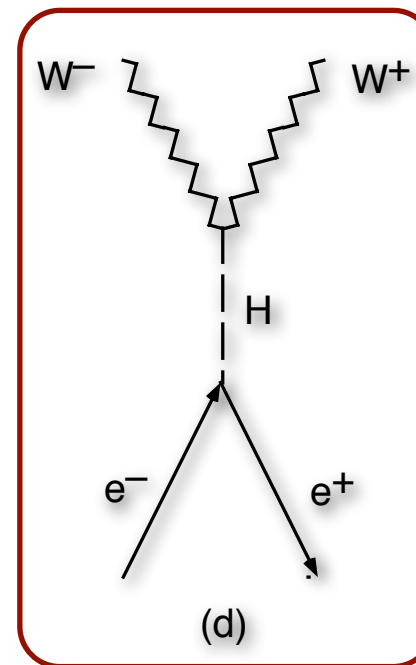
(a)



(b)



(c)



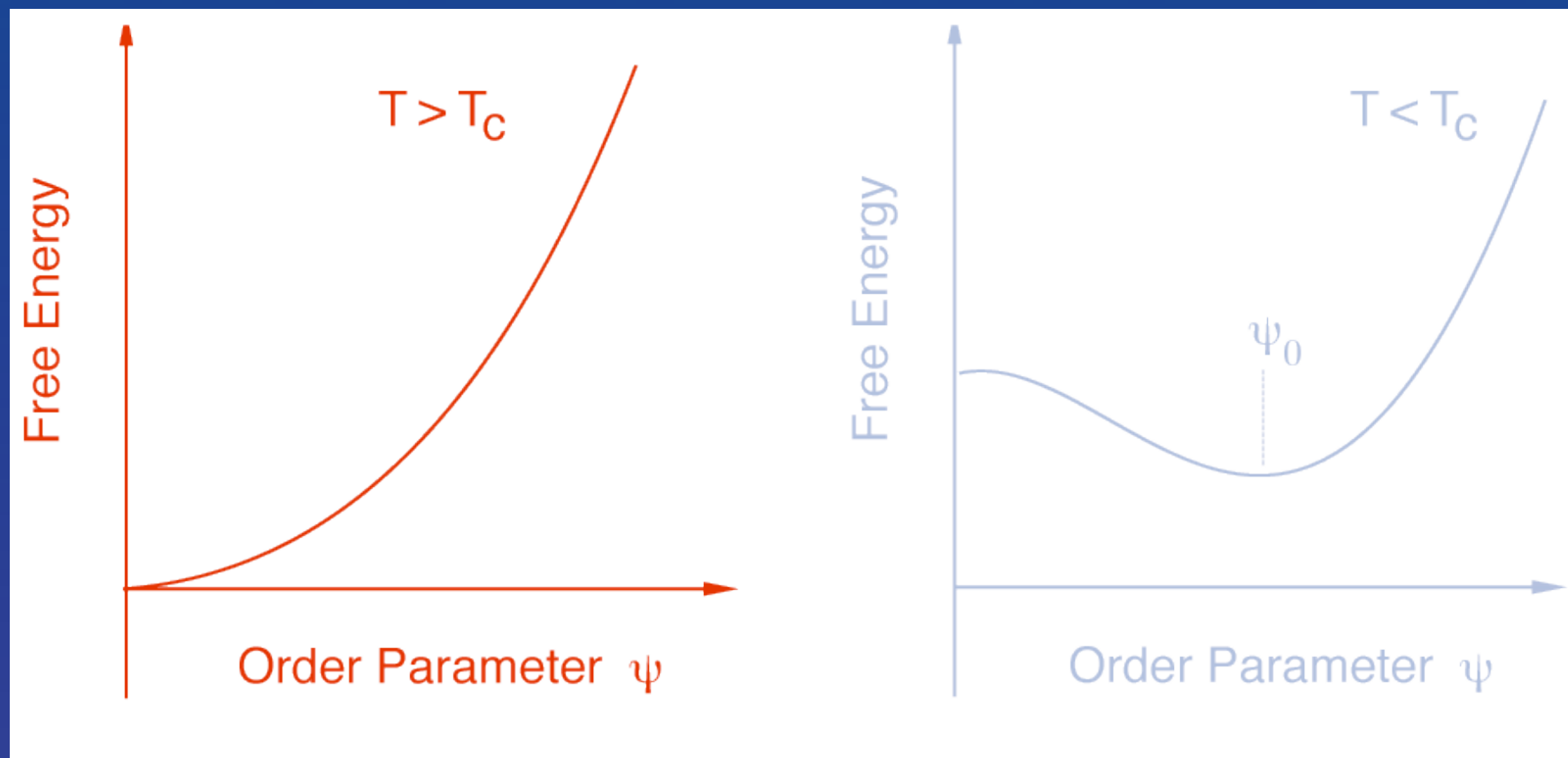
(d)

Massive weak
bosons:
Higgs boson

Meissner effect

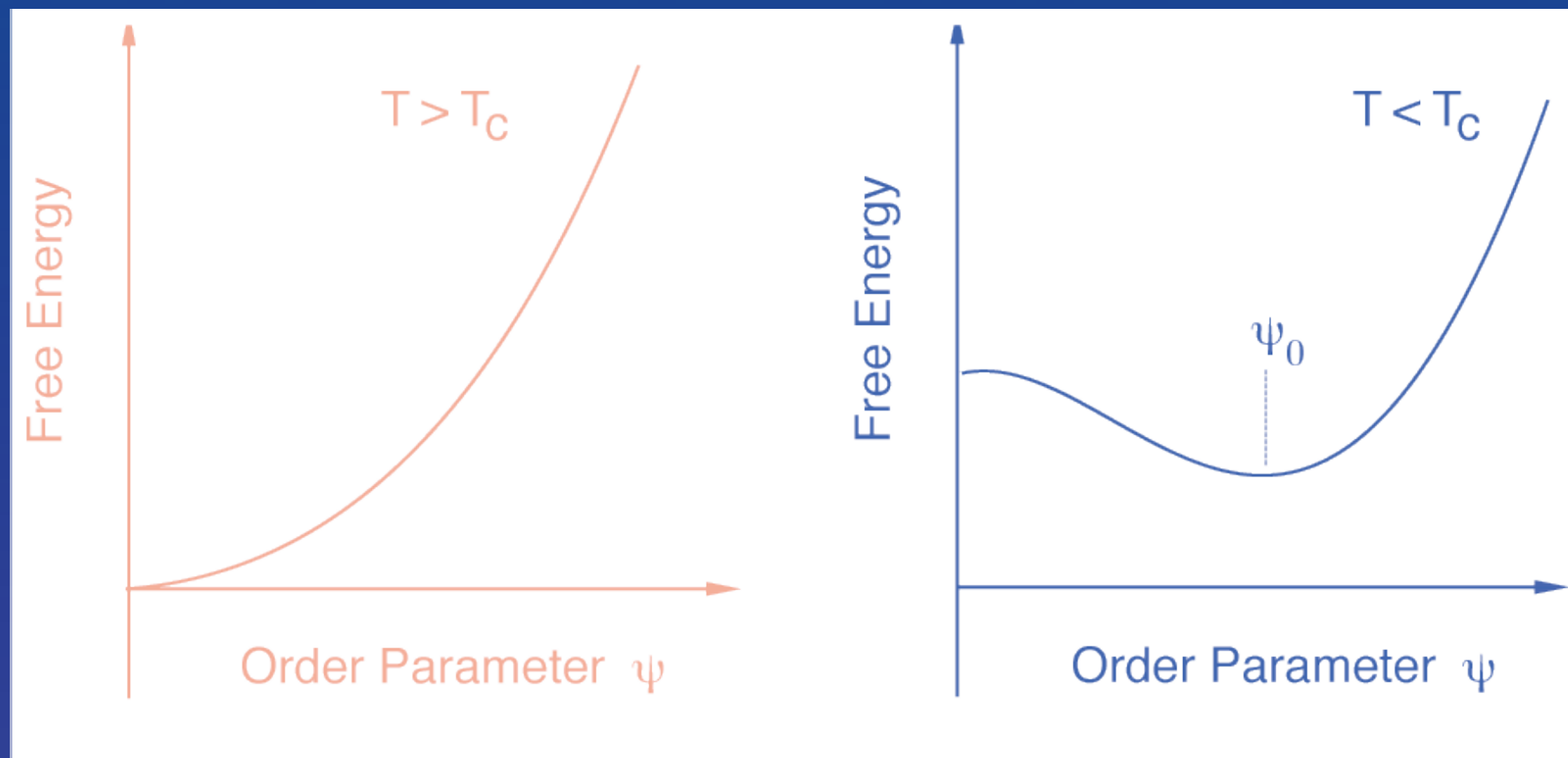
The agent of electroweak symmetry breaking represents a **novel fundamental interaction** at an energy of a few hundred GeV ...

We do not know the nature of the new force.



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We do not know the nature of the new force.



The Importance of the 1-TeV Scale

EW theory does not predict Higgs-boson mass

Thought experiment: *conditional upper bound*

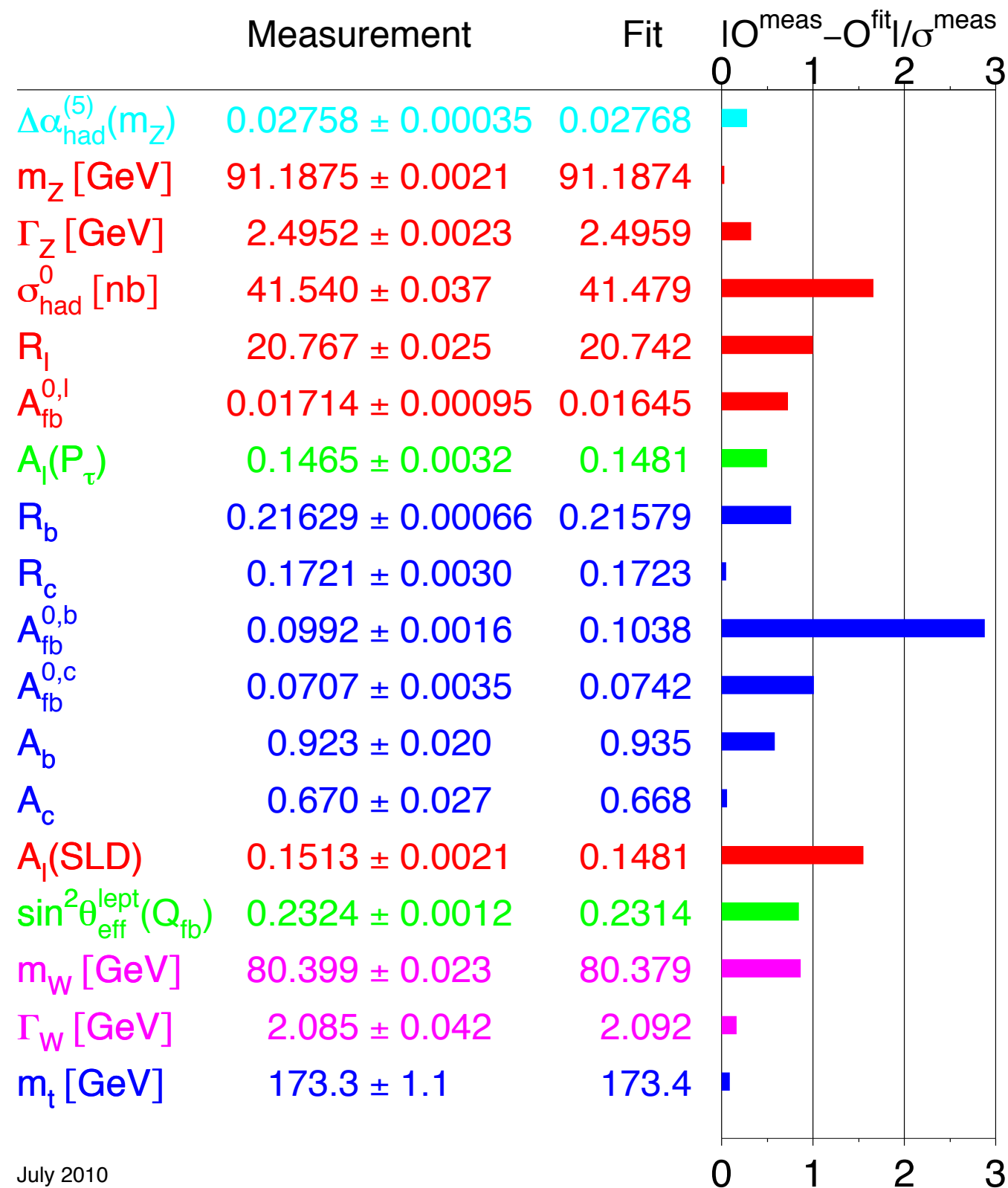
W^+W^- , ZZ , HH , HZ satisfy s-wave unitarity,

provided $M_H \leq (8\pi\sqrt{2}/3G_F)^{1/2} \approx 1 \text{ TeV}$

- If bound is respected, perturbation theory is “everywhere” reliable
- If not, weak interactions among W^\pm , Z , H become strong on 1-TeV scale

New phenomena are to be found around 1 TeV

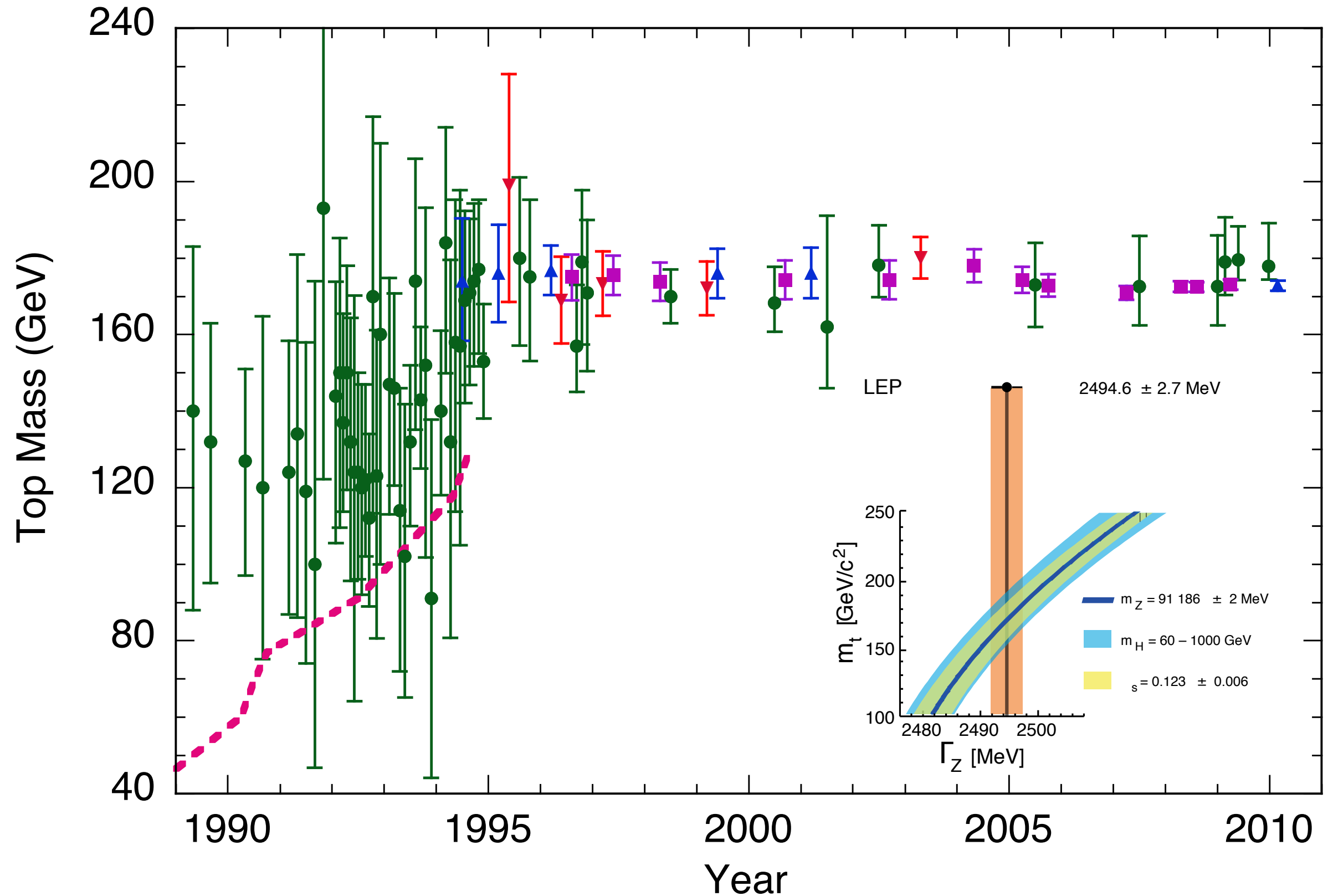
Precision Measurements Test the Theory ...



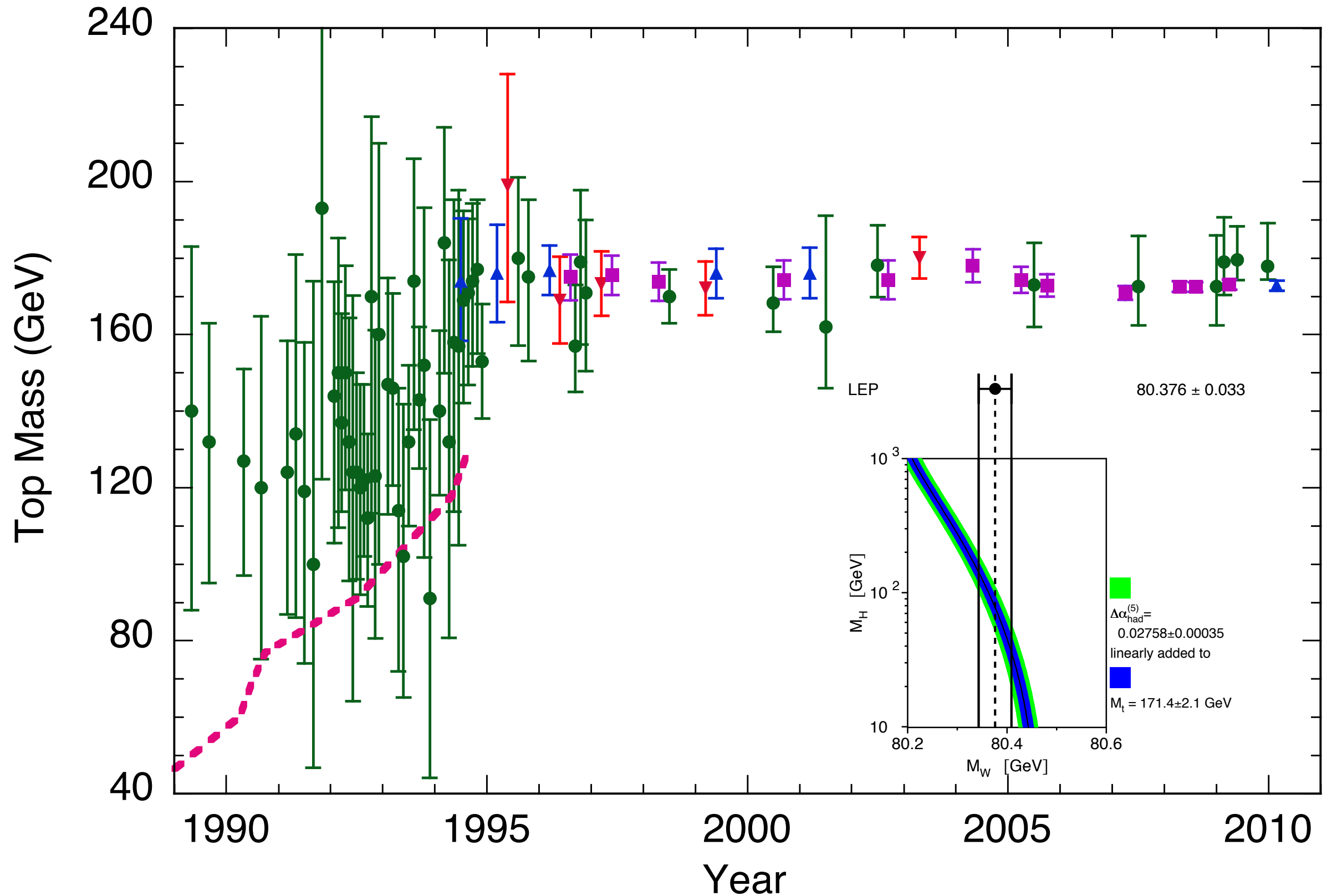
July 2010

LEP EW WG

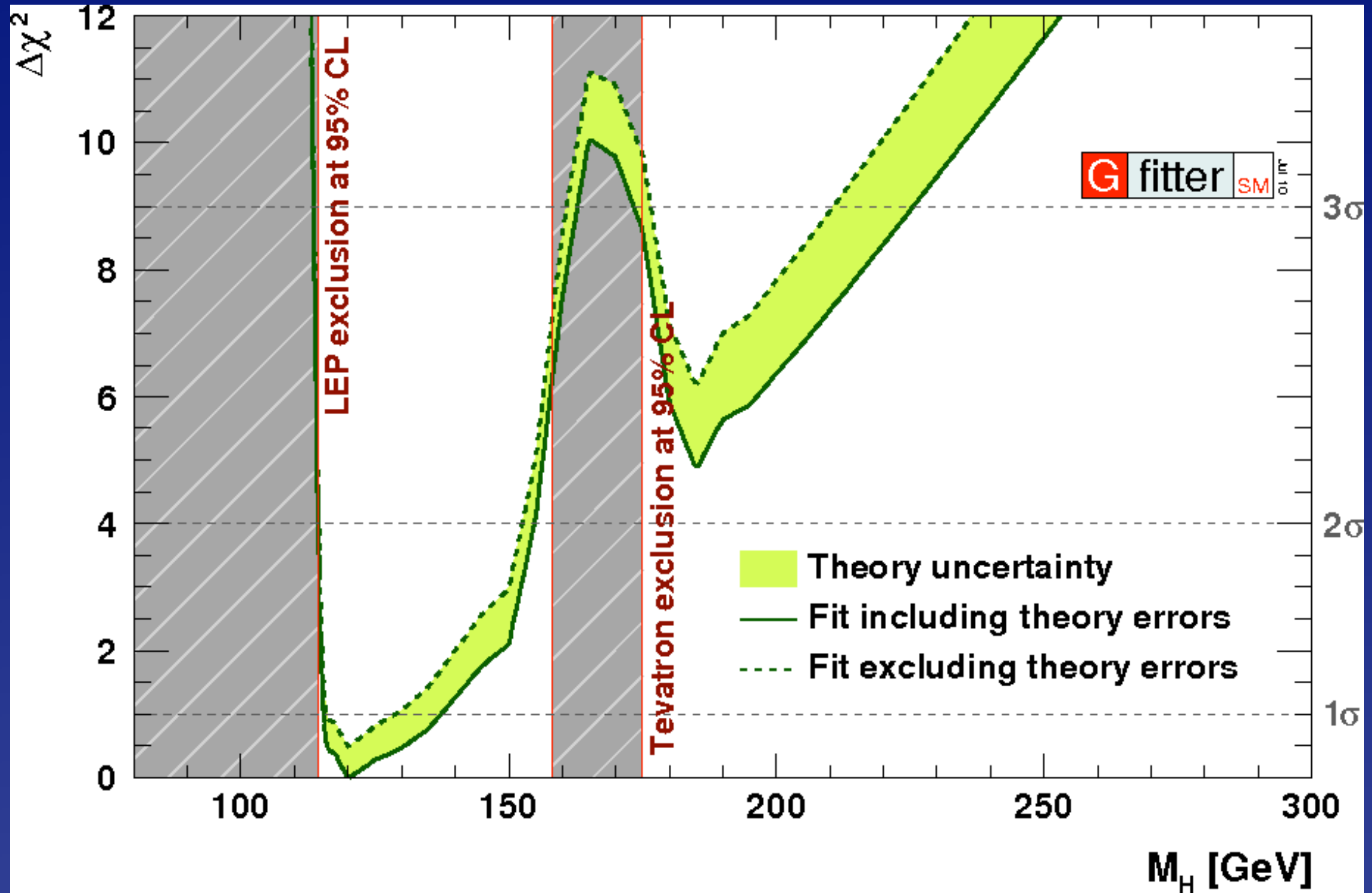
... and determine unknown parameters



... and determine unknown parameters



Where the (standard) Higgs boson might be



What is the nature of the mysterious new force that hides electroweak symmetry?

- *A force of a new character, based on interactions of an elementary scalar
- *A new gauge force, perhaps acting on undiscovered constituents
- *A residual force that emerges from strong dynamics among electroweak gauge bosons
- *An echo of extra spacetime dimensions

Which path has Nature taken?

Essential step toward understanding the new force that shapes our world:

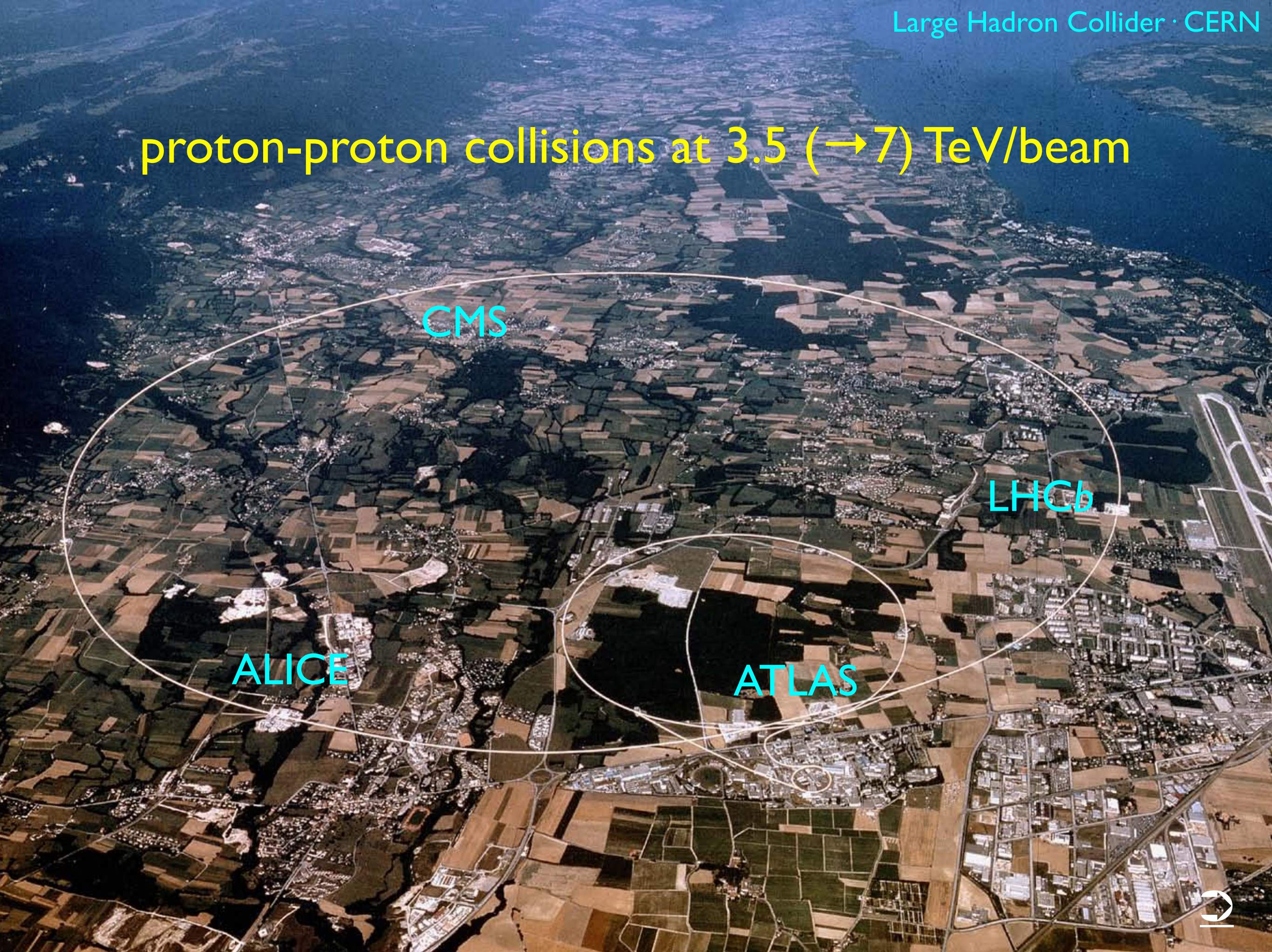
Find the Higgs boson and explore its properties.

- * Is it there? How many?
- * Verify quantum numbers (spin, parity, ...)
- * Does H generate mass for gauge bosons and for fermions?
- * How does H interact with itself?

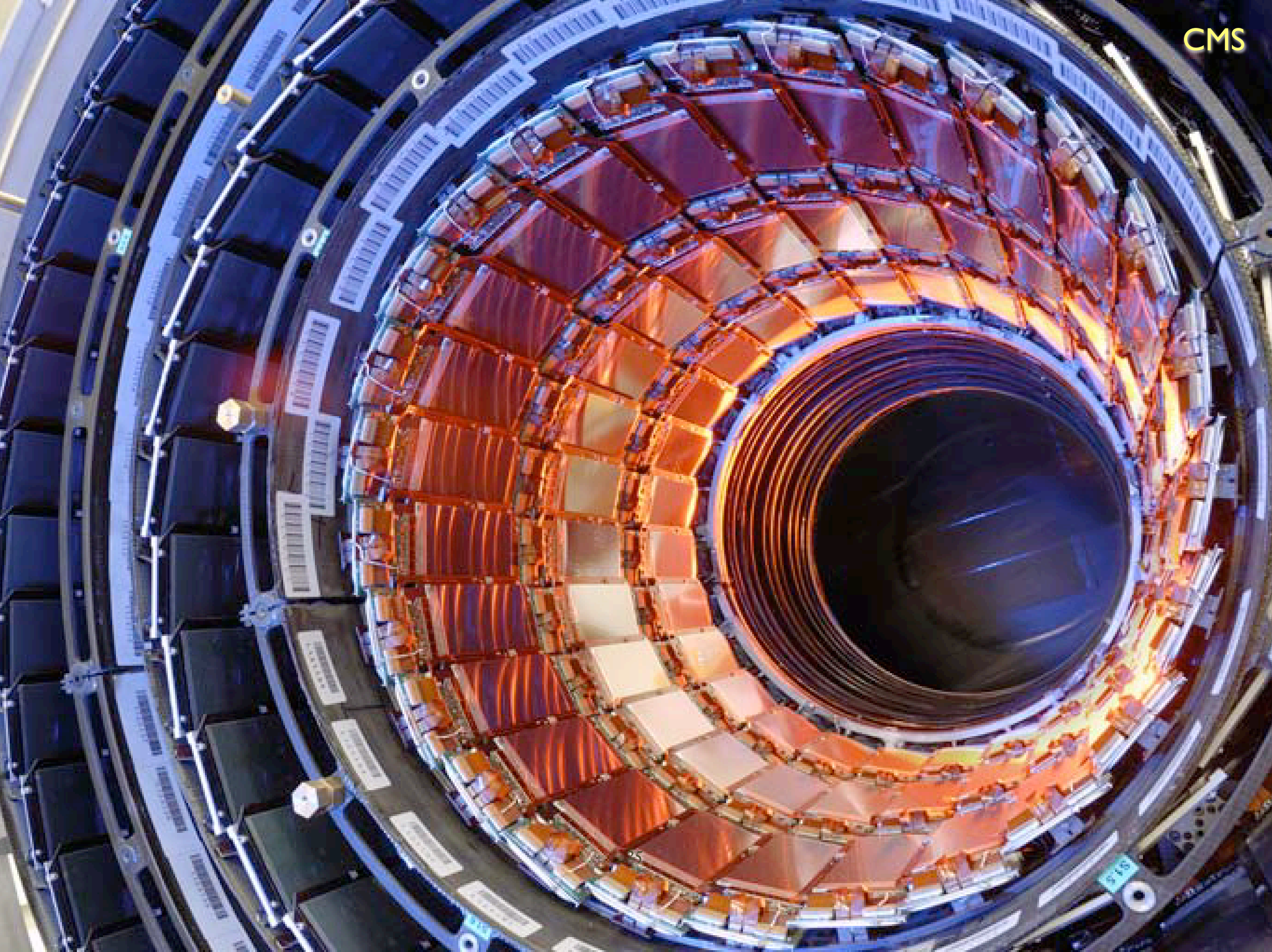
Finding the Higgs boson starts a new adventure!

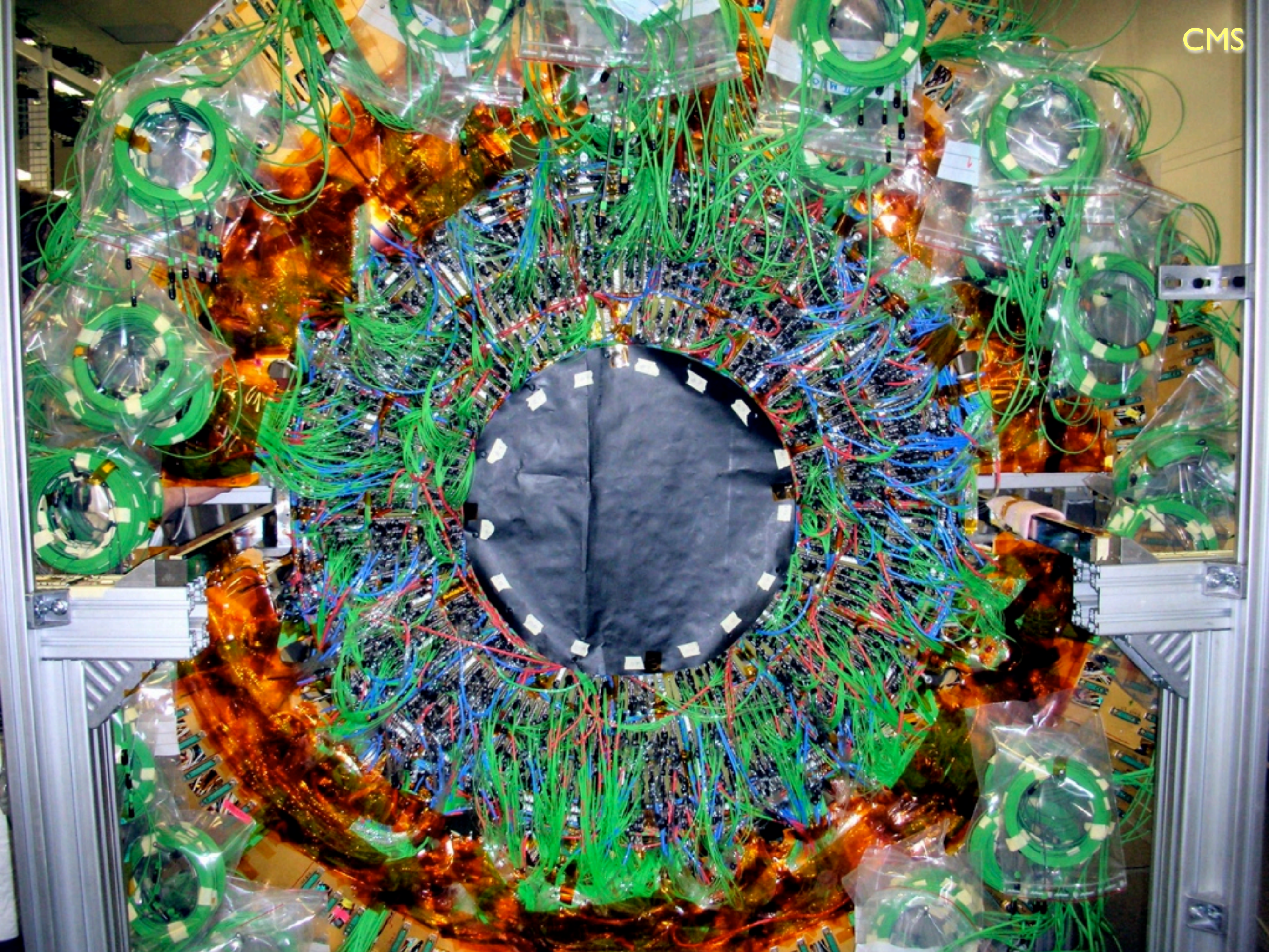


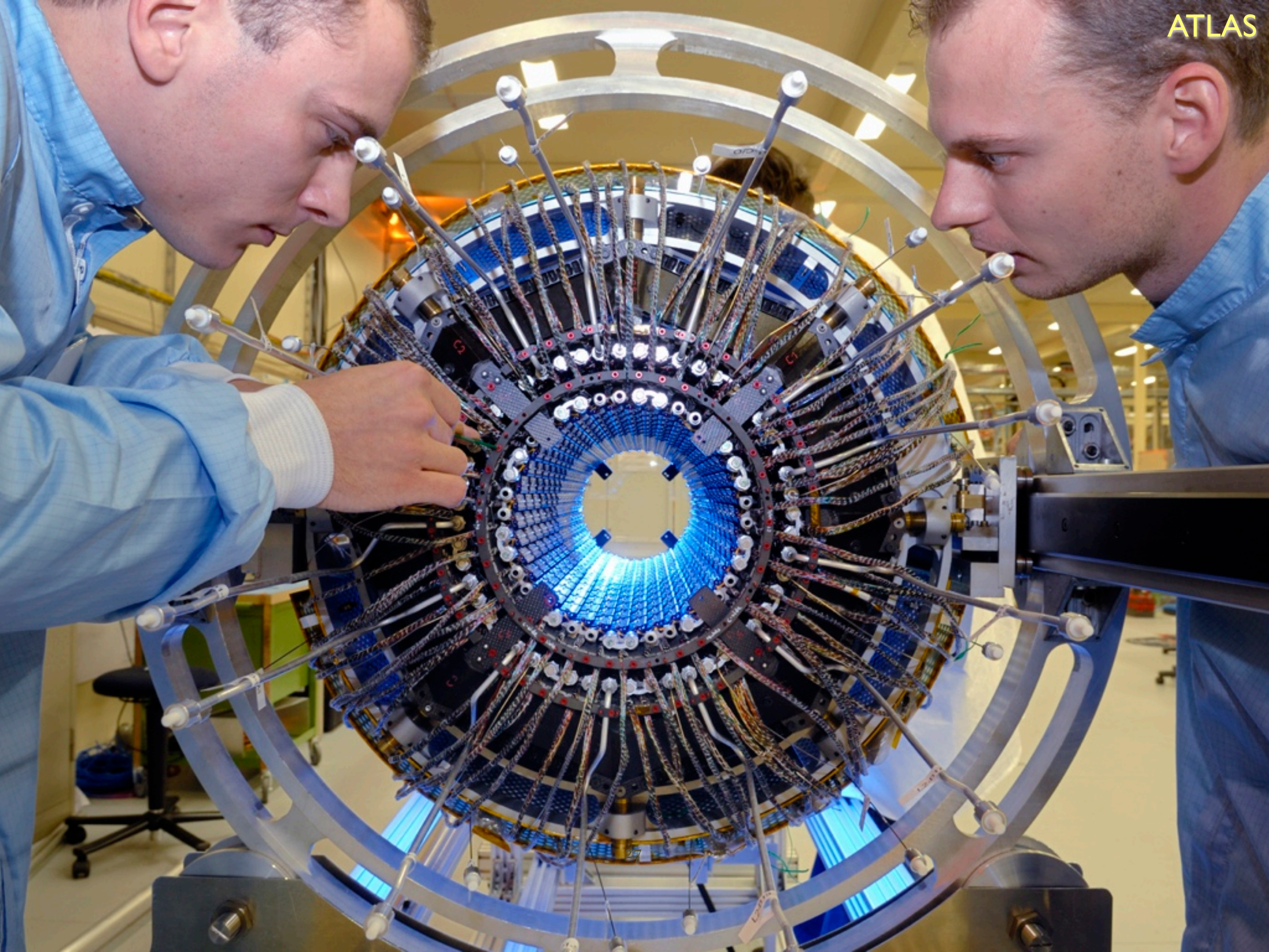
proton-proton collisions at 3.5 (\rightarrow 7) TeV/beam

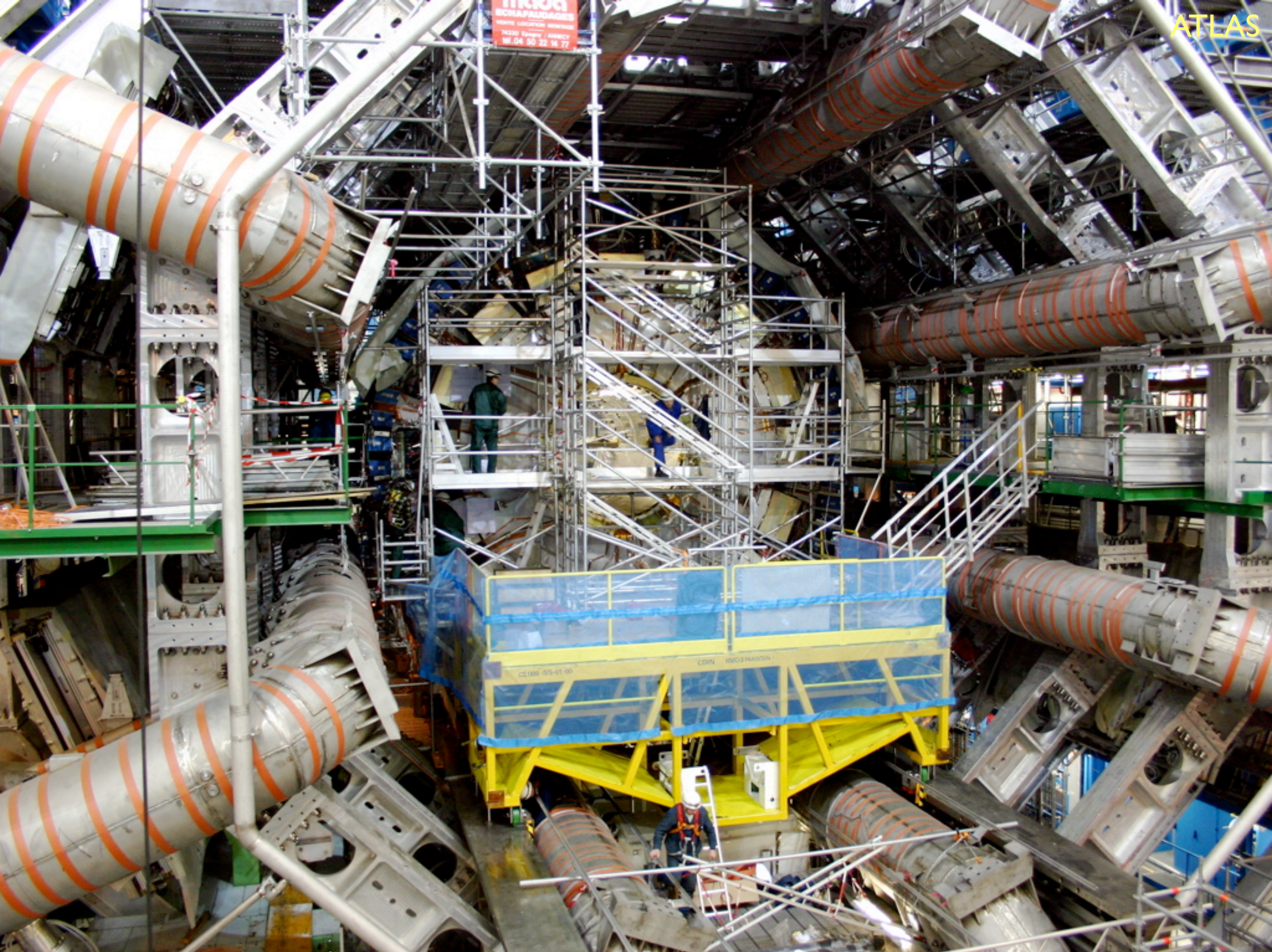


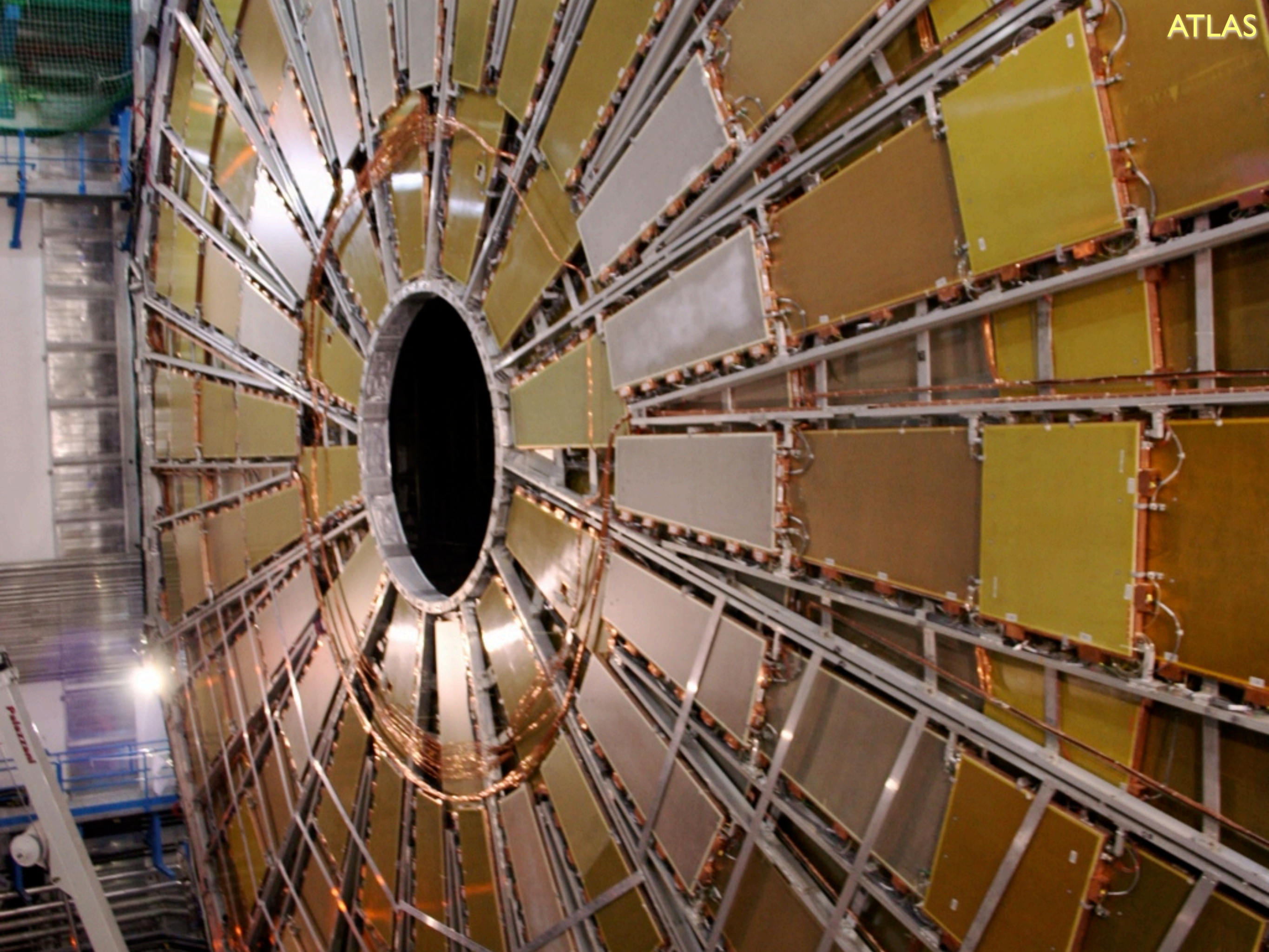












Why will it matter?

Understanding the everyday ...

Why atoms?

Why chemistry?

Why stable structures?

Imagine a world without a symmetry-breaking
(Higgs) mechanism at the electroweak scale

Without a Higgs mechanism ...

Electron and quarks would have no mass

QCD would confine quarks into protons, etc.

Nucleon mass little changed

*Surprise: QCD would hide EW symmetry,
give tiny masses to W, Z*

Massless electron: atoms lose integrity

*No atoms means no chemistry, no stable
composite structures like liquids, solids, ...*

*... character of the physical world
would be profoundly changed*

arXiv:0901.3958

Revolution:

The Meaning of Identity

Varieties of matter

- ▷ What sets masses and mixings of quarks and leptons?
- ▷ What is \mathcal{CP} violation trying to tell us?
- ▷ Neutrino oscillations give us another take, might hold a key to the matter excess in the Universe.

All fermion masses and mixings mean new physics

- ▷ Will new kinds of matter help us to see the pattern?

*What makes a top quark a top quark,
an electron an electron, a neutrino a neutrino?*

Parameters of the Standard Model

3 coupling parameters $\alpha_s, \alpha_{\text{em}}, \sin^2 \theta_W$

2 parameters of the Higgs potential

1 vacuum phase (QCD)

6 quark masses

3 quark mixing angles

1 CP-violating phase

3 charged-lepton masses

3 neutrino masses

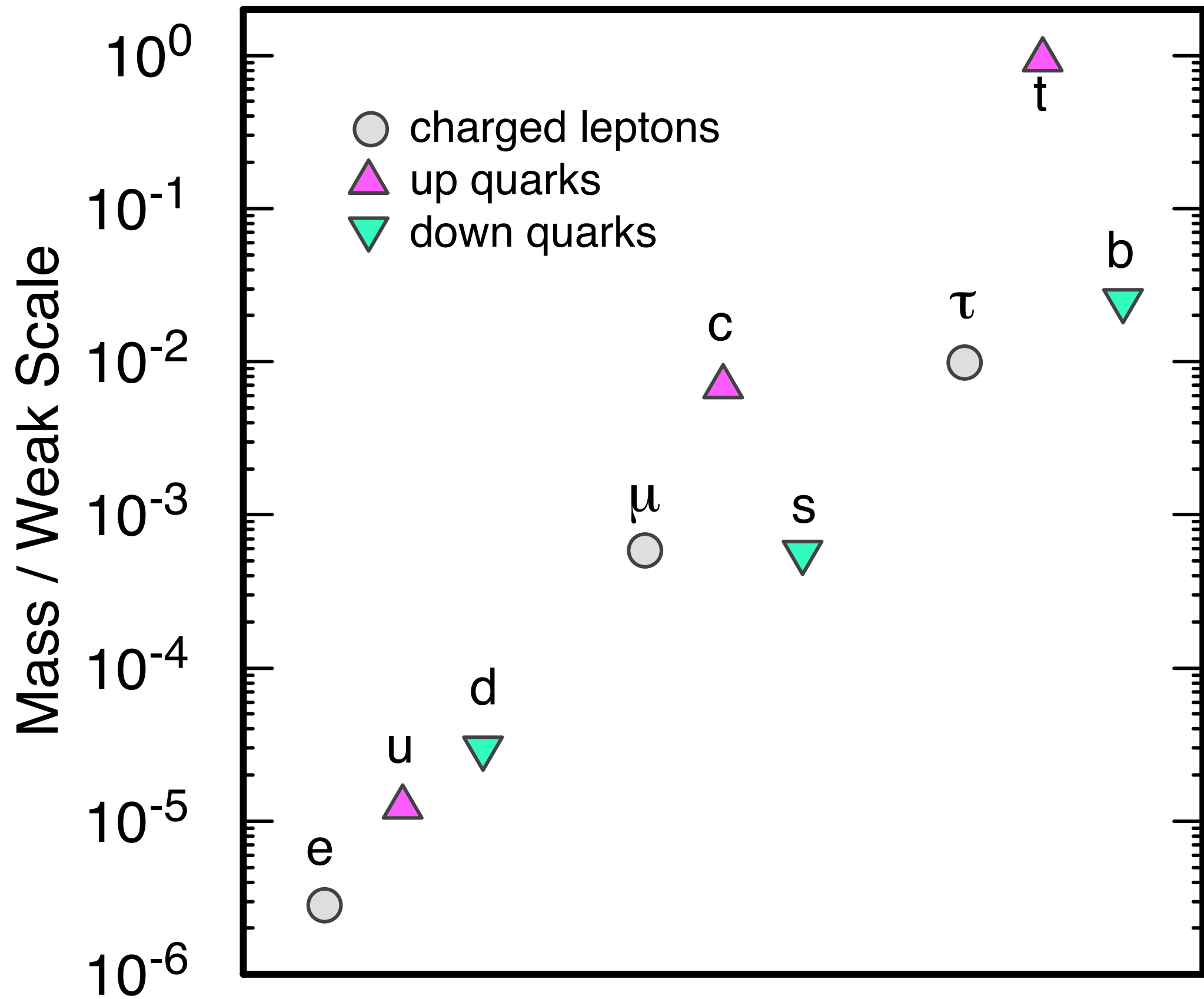
3 leptonic mixing angles

1 leptonic CP-violating phase (+ Majorana ...)

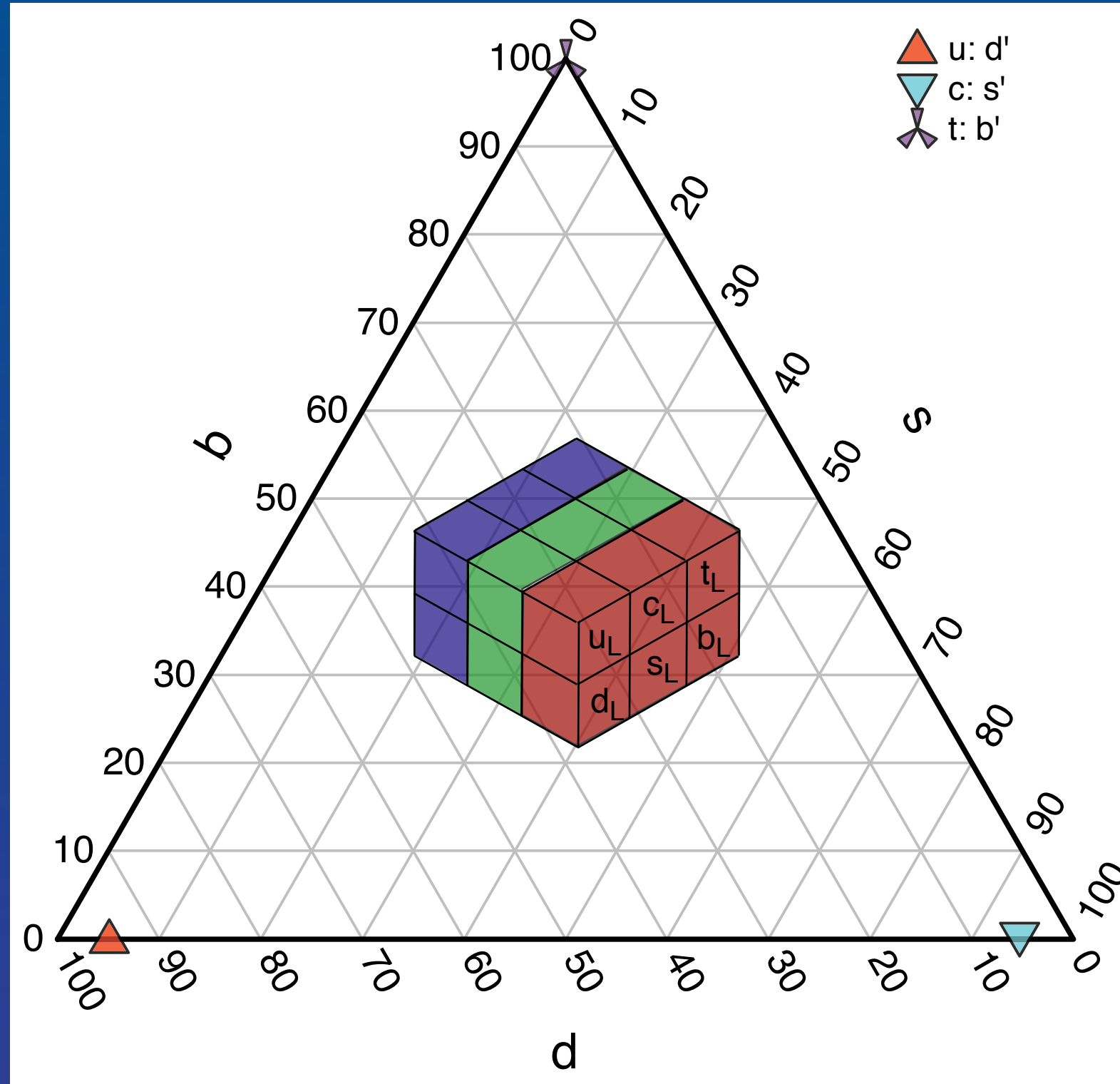
26⁺ arbitrary parameters

*Flavor physics may be
where we see, or diagnose,
the break in the SM.*



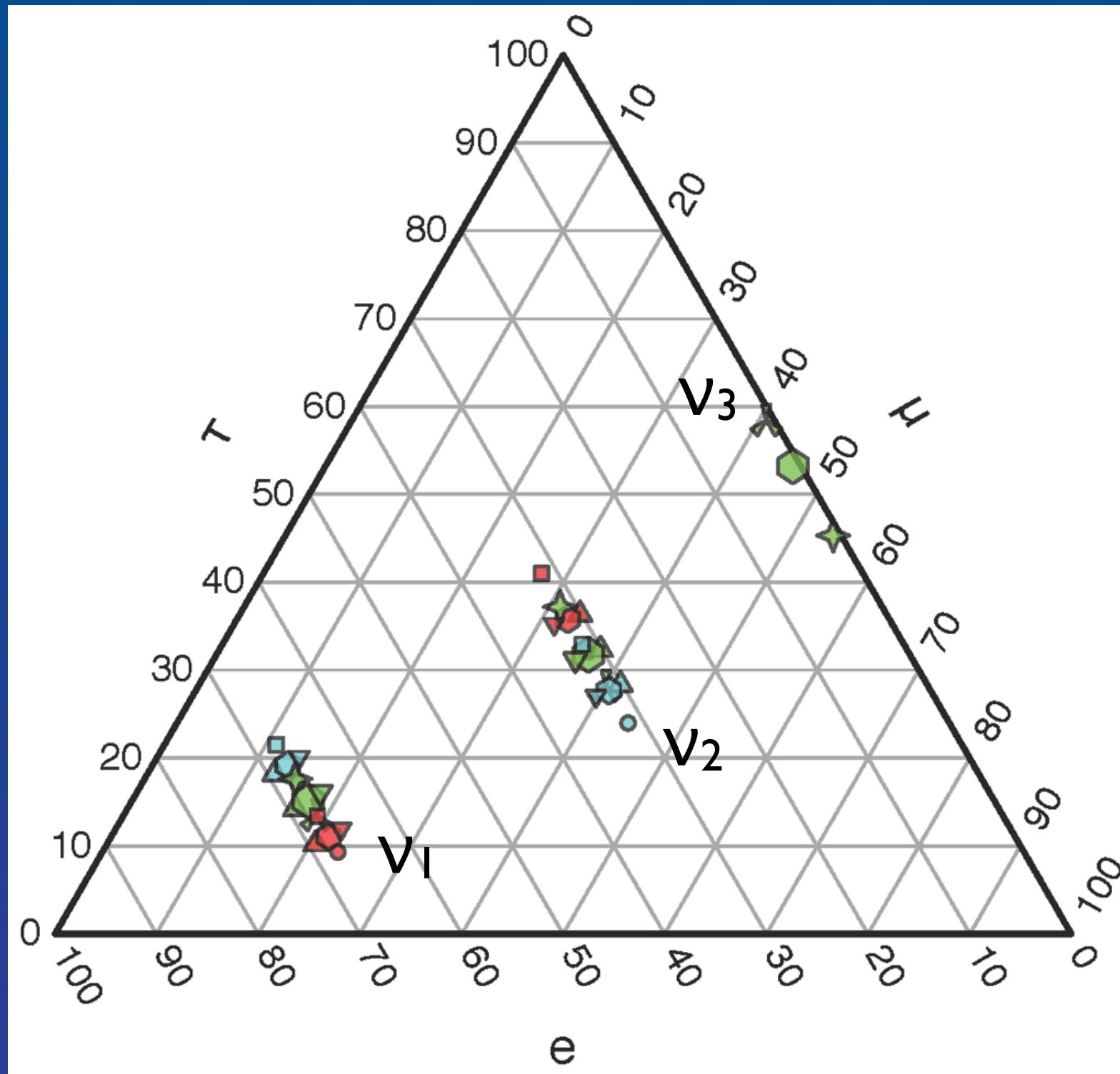


Quark family patterns: generations

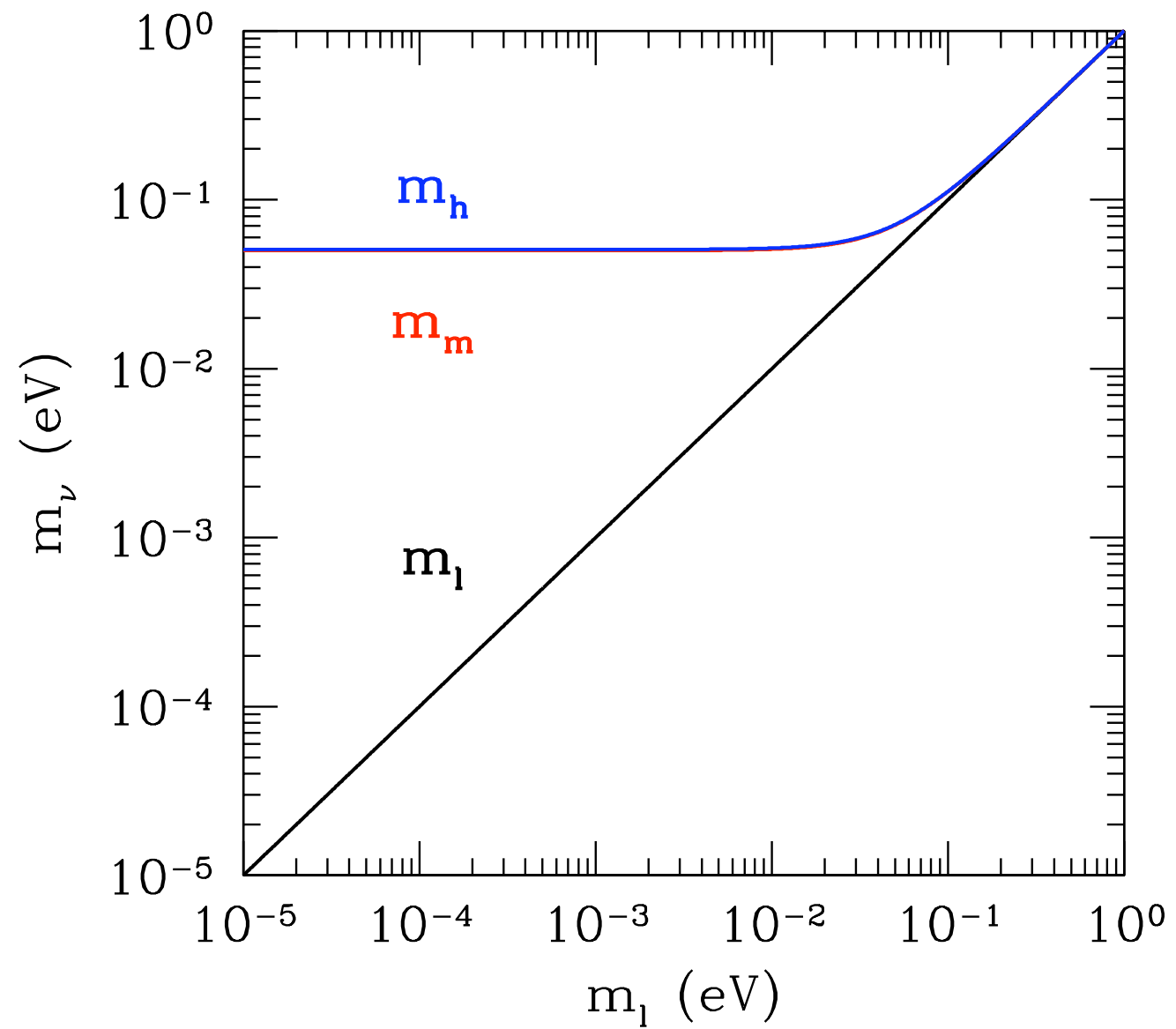
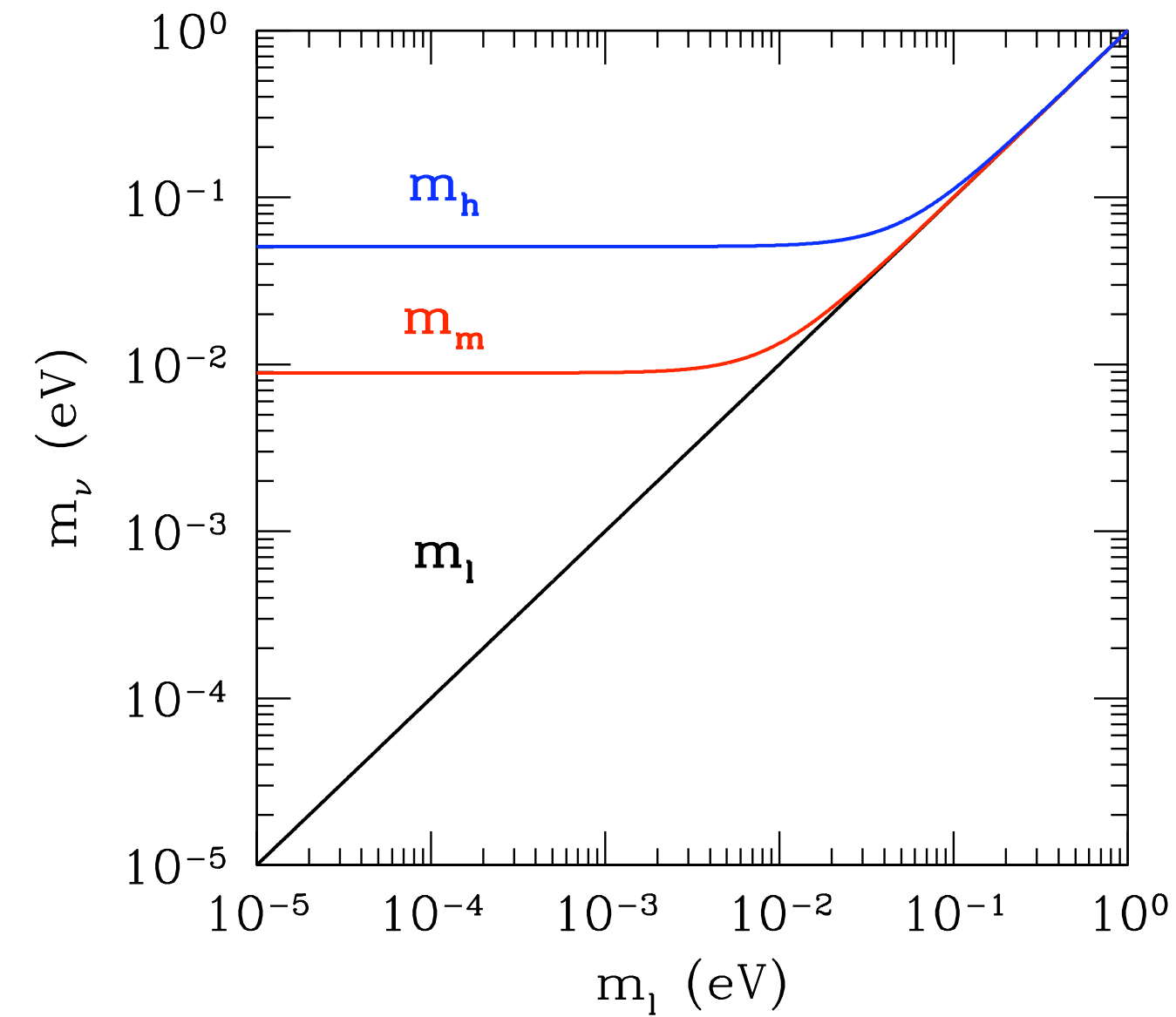


Veltman: Higgs boson knows something we don't know!

Neutrino family patterns



Neutrino Masses

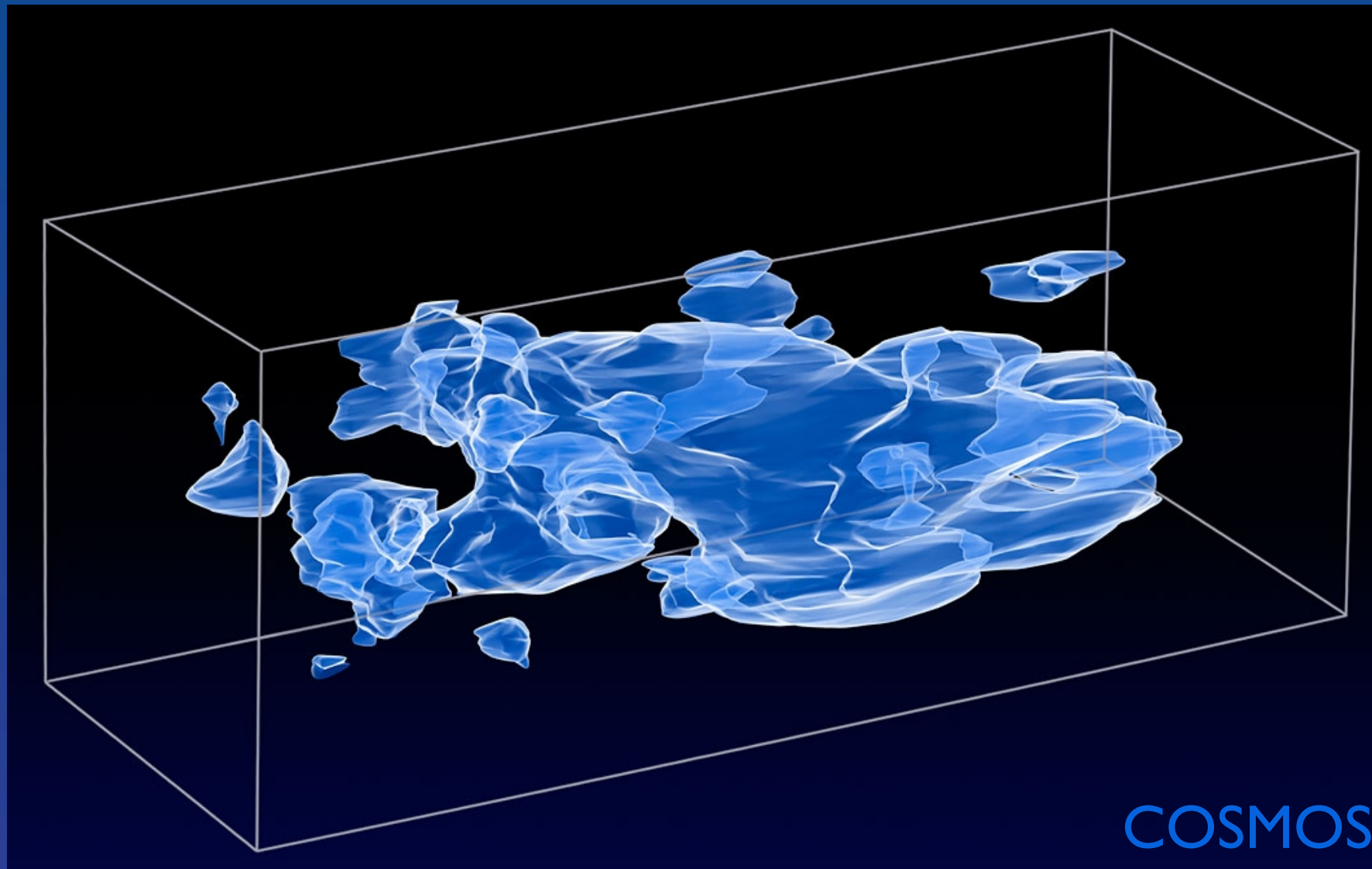




More

New Physics on the Fermi Scale?

If dark matter interacts weakly ...



... its likely mass is 0.1 to 1 TeV: *Fermi scale*

Many extensions to EW theory
entail dark matter candidates

Supersymmetry is highly developed, has several
important consequences:

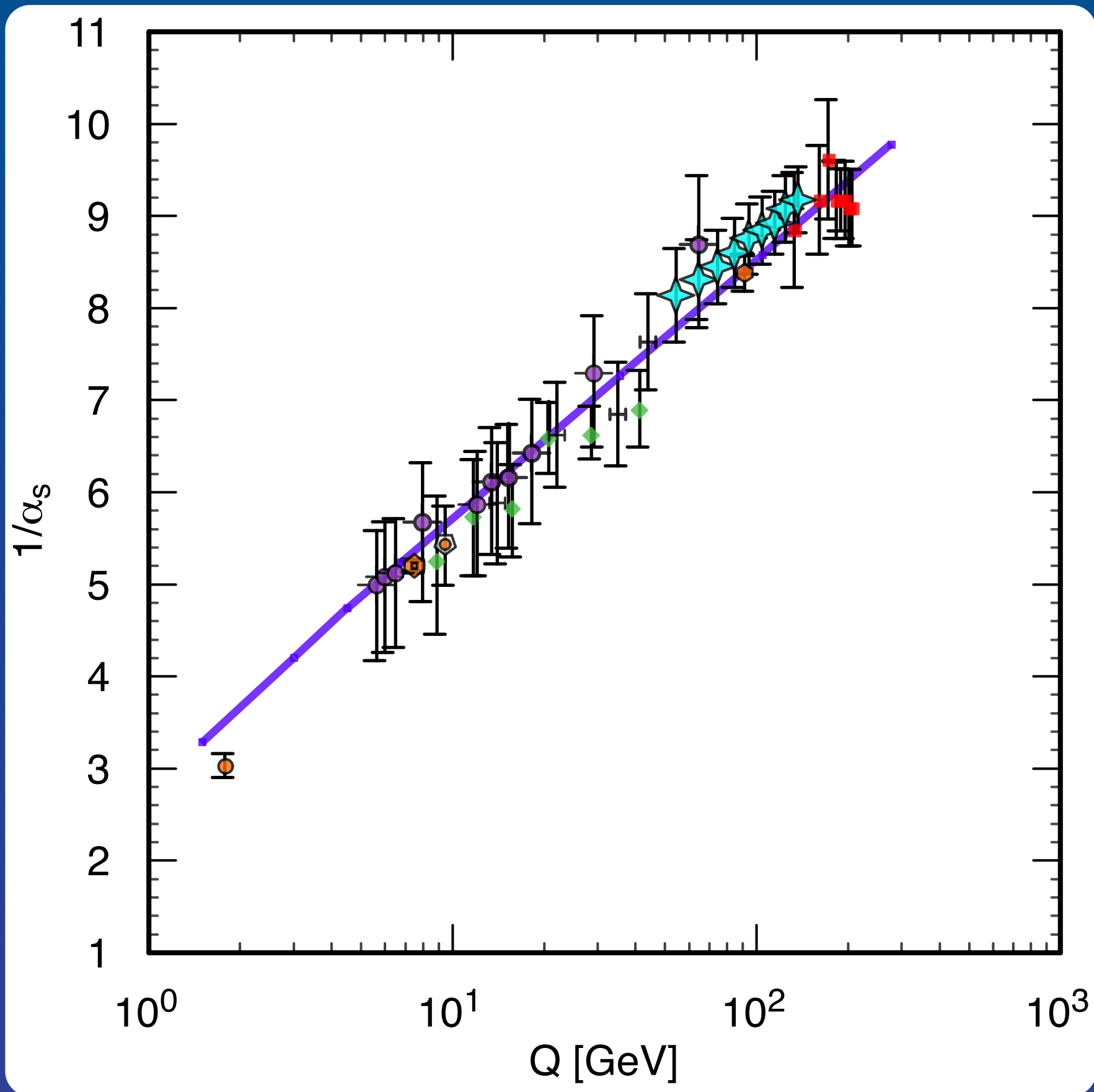
- *Predicts that Higgs field condenses,
breaking EW symmetry, if top is heavy
- *Predicts a light Higgs mass
- *Implies cosmological cold dark matter
- *In a unified theory, explains the values of
standard-model coupling constants

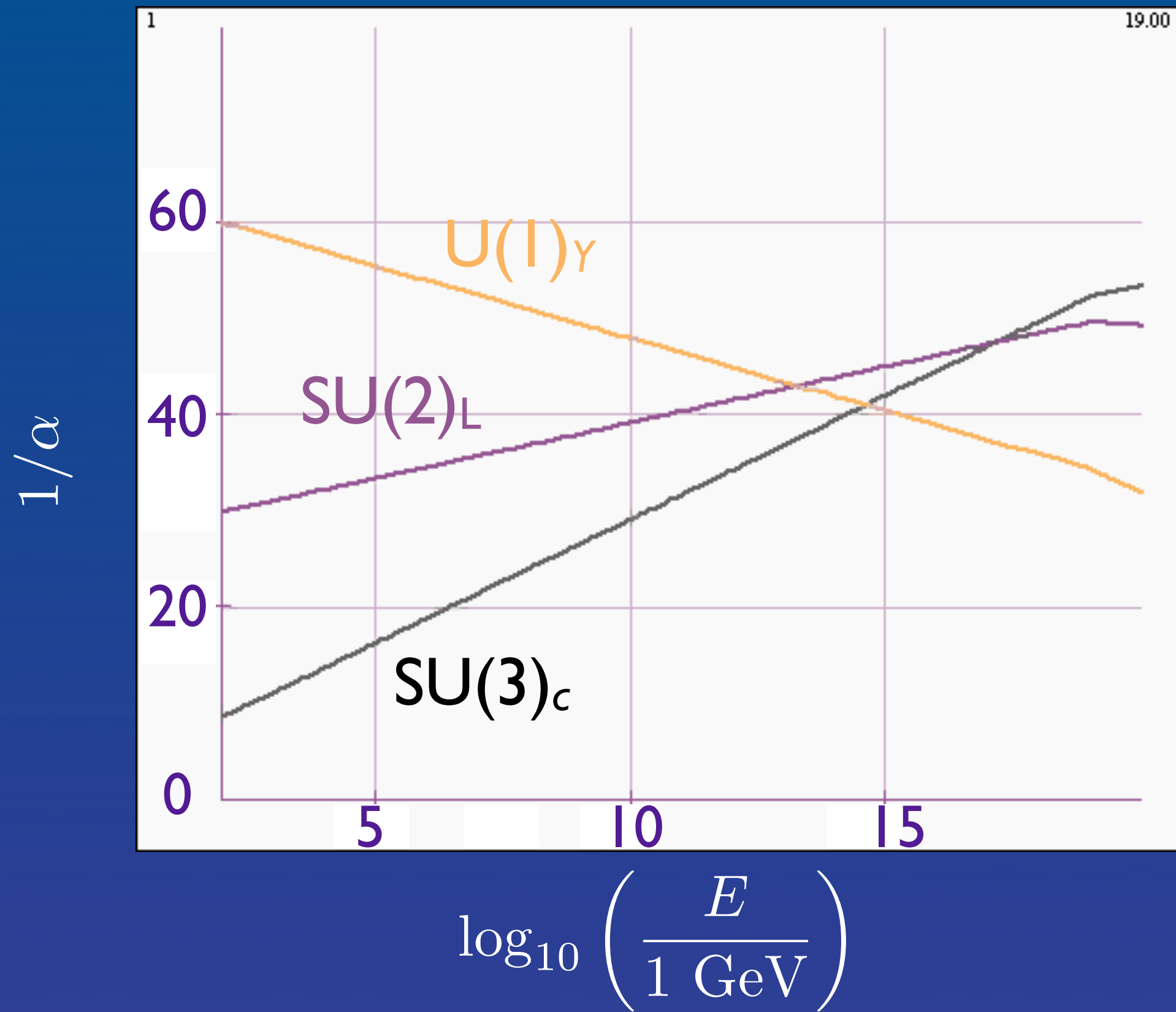
Revolution:

The Unity of Quarks & Leptons

- ▷ What do quarks and leptons have in common?
- ▷ Why are atoms so remarkably neutral?
- ▷ Which quarks go with which leptons?
- ▷ Quark-lepton extended family \rightsquigarrow proton decay:
SUSY estimates of proton lifetime $\sim 5 \times 10^{34}$ y
- ▷ Unified theories \rightsquigarrow coupling constant unification
- ▷ Rational fermion mass pattern at high energy?
(Masses run, too)

Evolution of the strong coupling “constant”





Why is empty space so nearly massless?

Natural to neglect gravity in particle physics

Gravitational ep interaction $\approx 10^{-41}$ EM

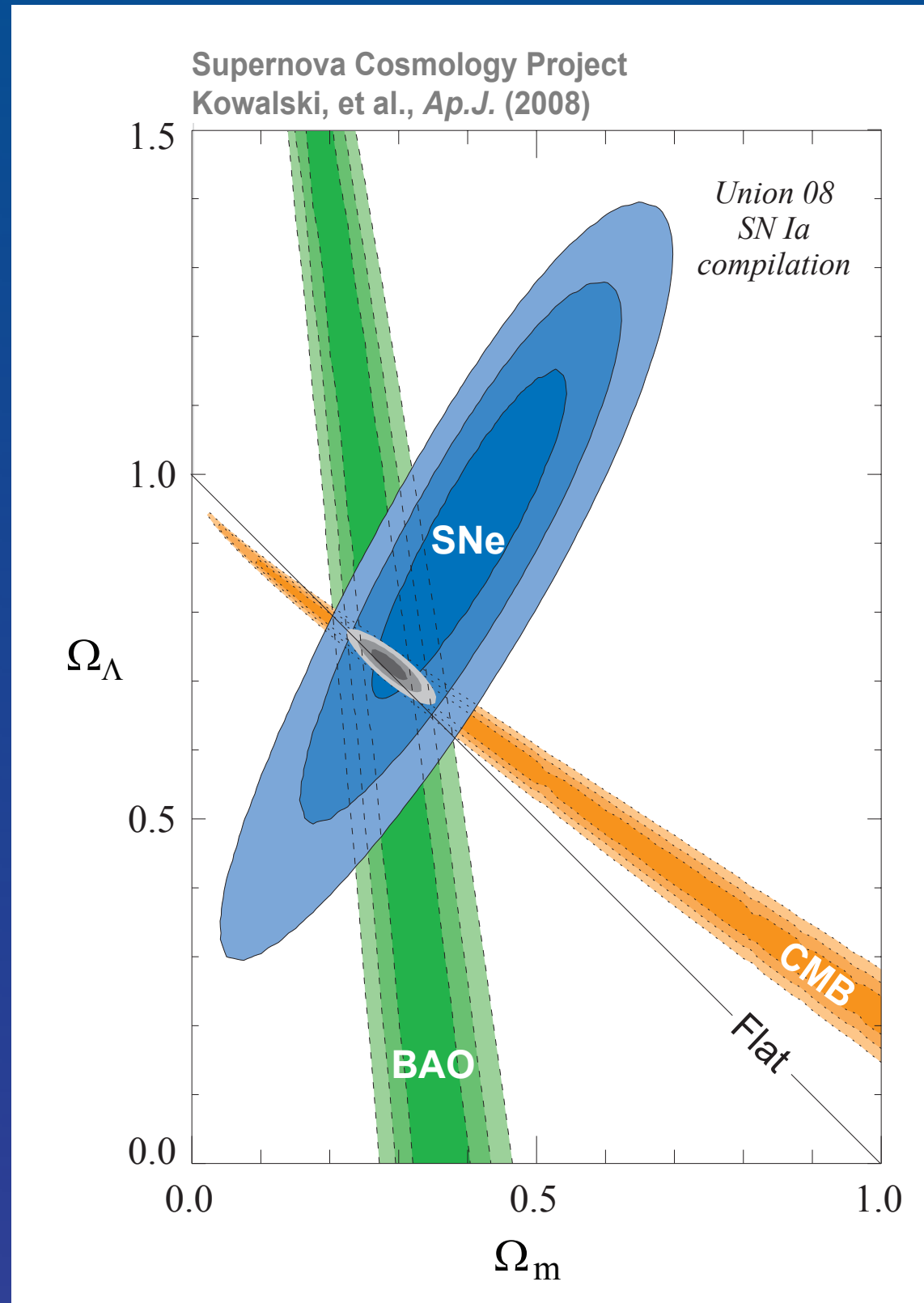
But gravity is not always negligible ...

Higgs field contributes uniform vacuum energy density

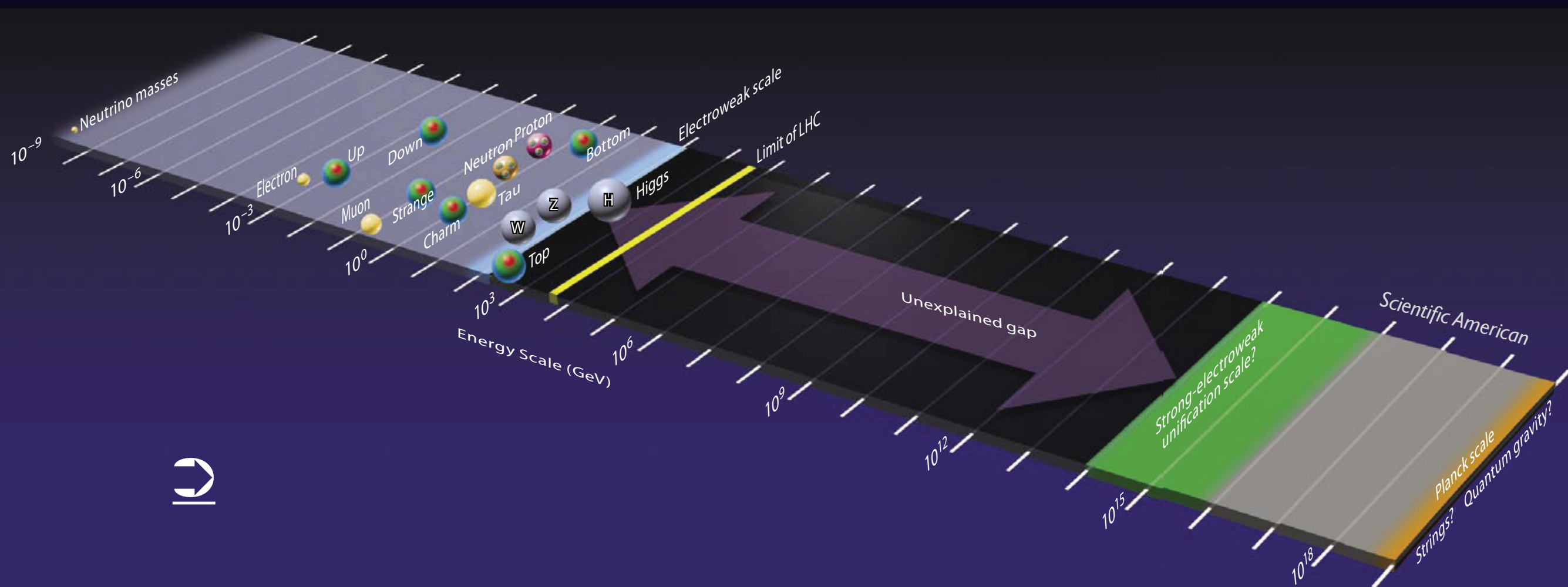
$$\rho_H \equiv \frac{M_H^2 v^2}{8} \geq 10^8 \text{ GeV}^4 \approx 10^{28} \text{ g/liter}$$

$$\text{Critical density } \rho_c \equiv \frac{3H_0^2}{8\pi G_{\text{Newton}}} \lesssim 10^{-26} \text{ g/liter}$$

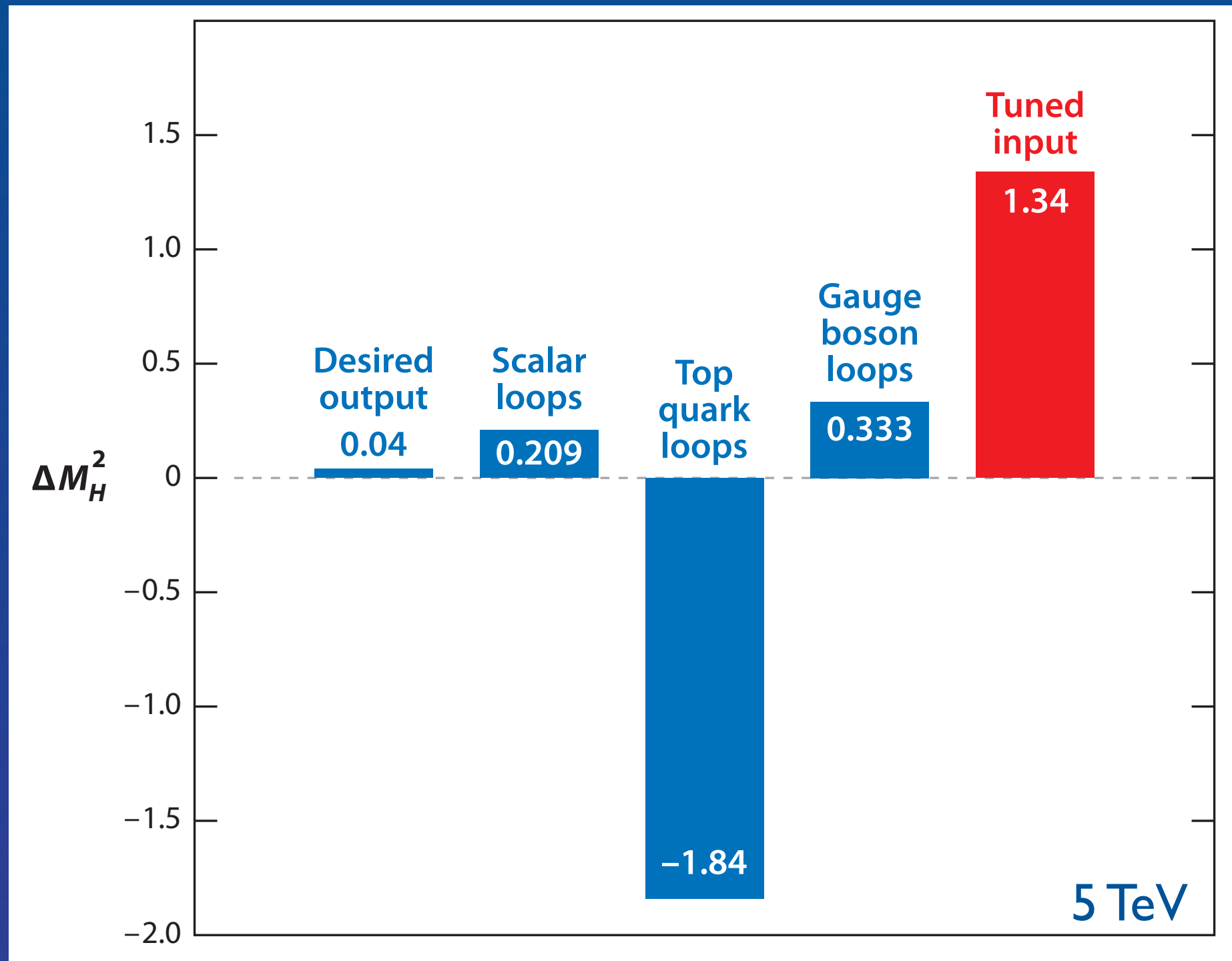
A chronic dull headache for thirty years ...



Another “small” challenge:
Does $M_H < 1 \text{ TeV}$ make sense?
The peril of quantum corrections



How to separate EW, higher scales?



How to separate electroweak, higher scales?

Extend electroweak theory on the 1-TeV scale ...

composite Higgs boson

technicolor / topcolor

supersymmetry

...

Ask instead why gravity is so weak

Revolution:

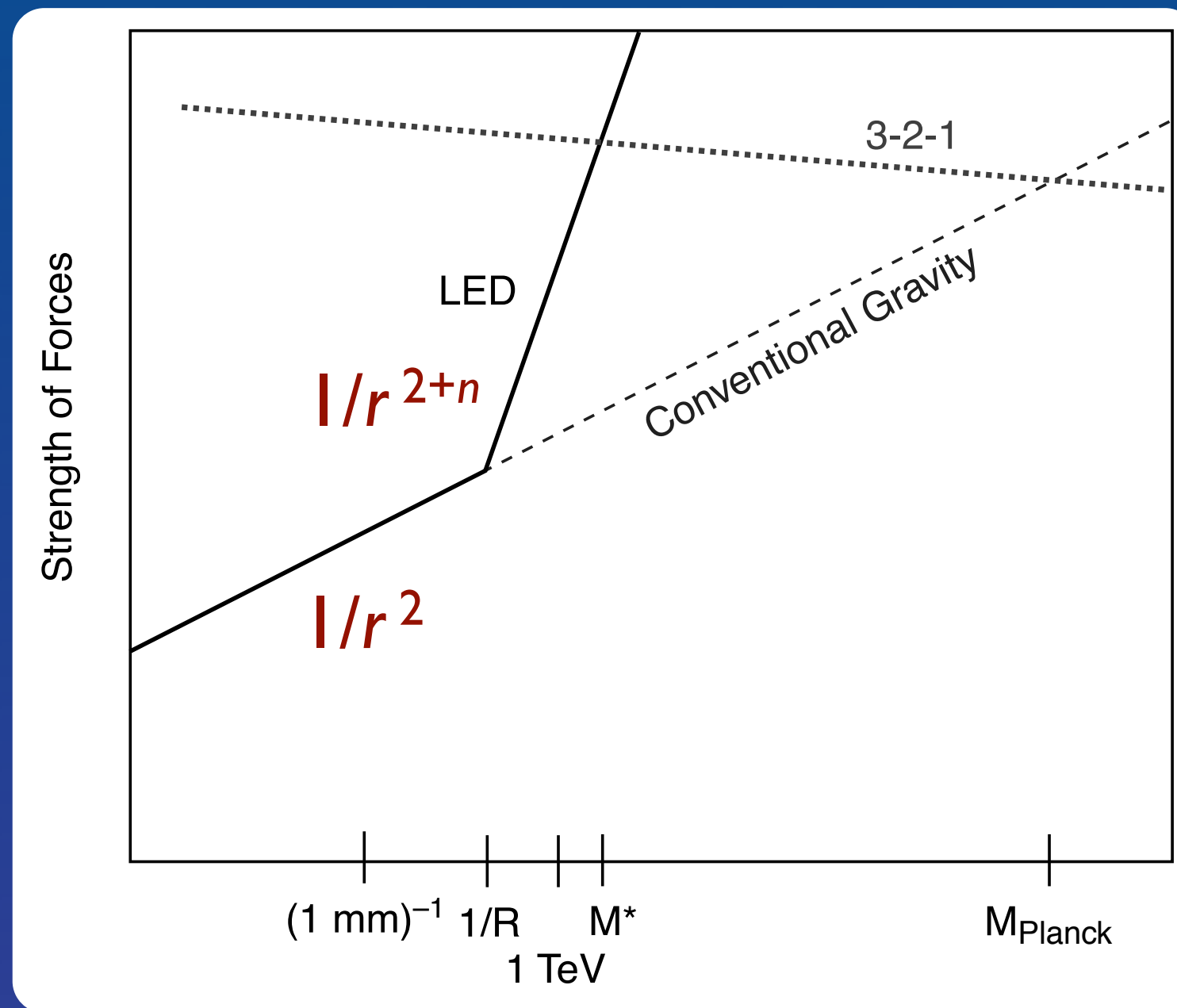
A New Conception of Spacetime

- ▷ Could there be more space dimensions than we have perceived?
- ▷ What is their size? Their shape?
- ▷ How do they influence the world?
- ▷ How can we map them?

string theory needs 9 or 10

Suppose at scale R ... gravity propagates in $4+n$ dimensions

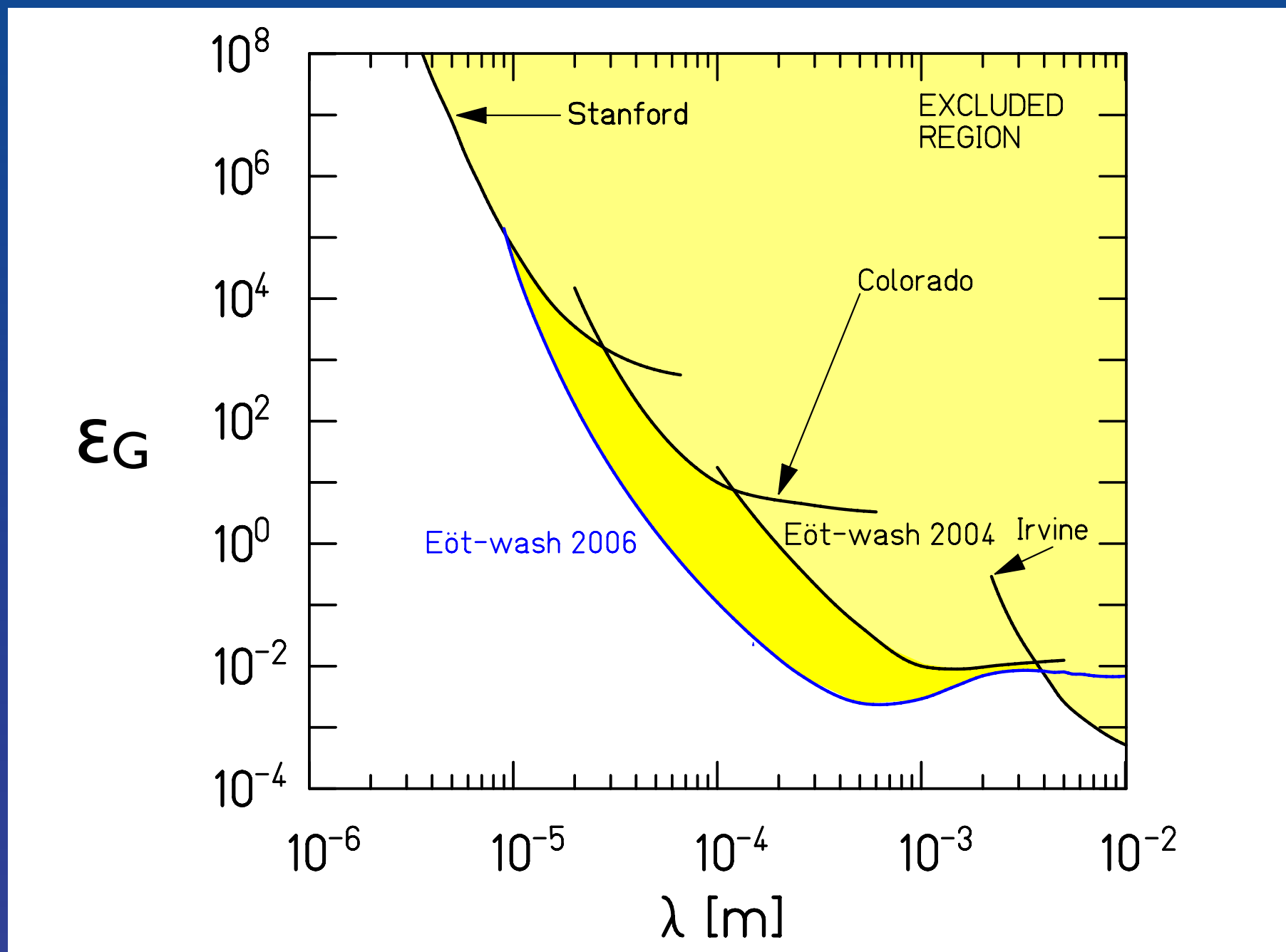
Gauss law: $G_N \sim M^{*-n-2} R^{-n}$ M^* : gravity's true scale



M_{Planck} would be a mirage!

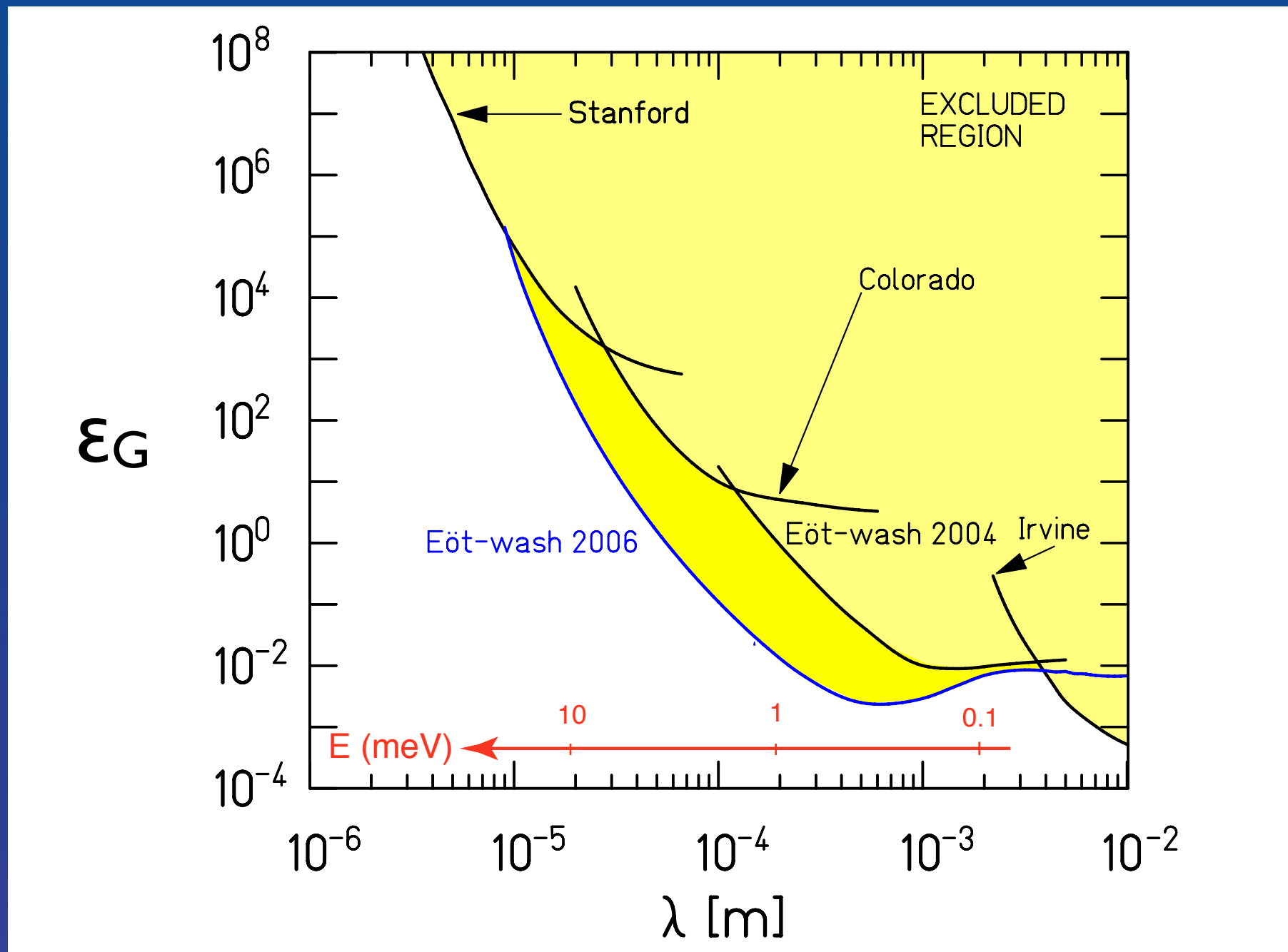
Gravity follows Newtonian force law down to ≈ 1 mm

$$V(r) = - \int dr_1 \int dr_2 \frac{G_{\text{Newton}} \rho(r_1) \rho(r_2)}{r_{12}} [1 + \varepsilon_G \exp(-r_{12}/\lambda_G)]$$



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Connections ...

[arXiv:0905.3187](#)

[Spektrum der Wissenschaft, 11.2008](#)